

## Article

# Voltage Changes in a Medium-Voltage Distribution Network Caused by the Connection of a Wind Farm

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## Abstract

This study aimed to analyse how wind-farm location and line-loading characteristics affect voltage variations in medium-voltage distribution networks. Simulations were performed in DIgSILENT PowerFactory using three 20 km radial MV lines with different conductor cross-sections. The wind farm was connected successively at selected line nodes, and its power was adjusted in each case to produce a 3% voltage rise at the point of connection. Three operating scenarios were considered: an unloaded line, a line with a resistive-inductive load and a line with a resistive-capacitive load. For the unloaded line, the voltage rise downstream of the wind farm remained constant at 3%, whereas the source's effect on nodes closer to the HV/MV substation diminished rapidly, with values ranging from 0.021% to 0.097%. Under load, the voltage-change profiles became non-linear, and the maximum deviations exceeded those observed for the unloaded line. For a resistive-inductive load, the voltage change reached approximately 3.1–3.3%, and the largest deviations occurred not at the point of connection but farther downstream. These findings demonstrate that wind-farm hosting capacity cannot be assessed solely from the voltage at the point of connection. In many cases, the 3% criterion is satisfied at the point of connection while the same threshold is exceeded elsewhere in the network. The full line voltage profile and load characteristics should therefore be considered when planning the integration of renewable energy sources into MV networks.

**Keywords:** medium-voltage distribution network; wind farm; voltage variation; distributed generation



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## 1. Introduction

Renewable energy deployment has expanded rapidly worldwide in recent years, driven by efforts to reduce greenhouse gas emissions, enhance energy security, and achieve climate policy objectives. According to analyses by the International Energy Agency (IEA), global installed renewable-energy capacity could increase approximately 2.7-fold by 2030 relative to 2022, with wind and photovoltaic technologies accounting for approximately 95% of this growth [1]. Wind power plays a particularly important role in the energy transition. Global installed wind-power capacity has already exceeded 1 TW, and record additions of new generating capacity have been reported in recent years. According to the

Global Wind Energy Council, 117 GW of new wind capacity was installed worldwide in 2024, one of the highest annual additions in the sector's history [2].

The rapid increase in the number of wind farms necessitates their integration into existing power networks. A substantial proportion of new generating sources are connected to distribution networks that were originally designed for unidirectional power flow. The growing penetration of distributed generation is increasingly leading to bidirectional power flows and may even result in electricity being exported to the upstream network. These developments affect power-flow patterns, short-circuit current levels, technical losses and the operating conditions of protection and voltage-control equipment [3].

One of the principal issues associated with wind-farm integration is voltage variation within the power system [4]. Its magnitude and character depend on fluctuations in generated power, network parameters and the turbine's reactive-power control strategy [5]. A wind farm connected to a radial network influences active- and reactive-power flows, voltage levels, network losses and the operating conditions of protection devices [6]. As the share of renewable generation in national power systems increases, maintaining voltage within prescribed limits becomes increasingly important [7], particularly in distribution networks with low short-circuit capacity and long feeders [8]. In a conventional radial network, power flows from the supply substation to consumers, whereas local generation may cause reverse power flow [8,9]. This changes the operating conditions of a network originally designed for unidirectional power transfer. Consequently, a generating source may alter currents in individual line sections, reactive power flows, and voltages at neighbouring nodes [6,8].

In the absence of local generation, voltage decreases with distance from the source due to voltage drops across the line impedance [10]. The magnitude of the drop depends on current, conductor parameters and load characteristics [11]. In long MV feeders, this effect may be particularly pronounced near the end of the line. Commissioning a wind farm can reduce loading on upstream line sections, lower network losses, and improve the voltage profile [12,13]. In many cases, local generation reduces the power imported from the supply substation, thereby decreasing Joule losses and limiting voltage drops at remote network nodes [12].

Conversely, when generation is high and local electricity demand is low, voltage may exceed permissible limits [8,14]. This situation occurs particularly during periods of low demand, when the wind farm's output exceeds local demand. Under these conditions, part of the generated power is exported to the supply substation, potentially reversing the power flow and causing voltage limits to be exceeded near the source connection point [8,9]. The problem becomes increasingly significant as more renewable sources are connected to distribution networks. The voltage level depends on both the active power generated and the reactive-power control strategy, as described by the following relationship [15]:

$$\Delta U \approx \frac{R_{\text{grid}} \cdot P + X_{\text{grid}} \cdot Q}{U_n} \quad (1)$$

where  $R_{\text{grid}}$  and  $X_{\text{grid}}$ —network resistance and reactance [ $\Omega$ ], respectively;  $P$ —active power [W];  $Q$ —reactive power [VAr];  $U_n$ —nominal network voltage [V].

In meshed networks, the effect of a wind farm on voltage is more complex because power can flow along multiple paths [16,17]. Wind generation changes current distribution, power losses and the voltage profile across a wider area of the system [18,19]. Unlike radial networks, in which power normally follows a single path, a change in generation at one point in a meshed network may simultaneously affect the operating conditions of several lines. The entire network must therefore be analysed rather than only the immediate vicinity of the source.

An increase in generation may cause a local voltage rise, particularly when consumer demand is low, and the resistive component of network impedance is high [8]. Voltage changes are not uniform across all nodes, because they depend on network configuration, loading level, short-circuit power and the voltage-control method [14,20,21]. The location of the source relative to the principal load centres and regulating devices, such as transformers equipped with on-load tap changers (OLTCs), is also important. In networks with high distributed generation penetration, effective voltage regulation requires advanced OLTC control systems that account for variable power flow and local network operating conditions. Otherwise, bidirectional power flows may cause suboptimal regulator operation and deteriorate voltage conditions. Consequently, two sources with the same rated power, connected at different points in the network, may produce substantially different voltage changes.

Modern wind farms incorporate power-electronic converters that can regulate power factor, reactive power or voltage at the point of connection [22,23]. They may therefore not only cause voltage changes but also contribute actively to voltage stabilisation. Contemporary turbines comply with grid-code requirements to provide system services, including voltage support and operation under variable network conditions [23]. The effectiveness of this control depends, among other factors, on converter parameters, operator requirements and the local short-circuit capacity of the network [24]. In weak distribution networks, even small changes in reactive power may cause substantial voltage variations, whereas the effect is much less pronounced in networks with high short-circuit capacity.

The inherent variability of wind generation is another important factor affecting voltage [25]. Changes in wind speed alter the power injected into the network, leading to dynamic power-flow changes, periodic voltage deviations and, in some cases, flicker [26,27]. The severity of these effects depends on local wind conditions, turbine technology, and power network parameters. Rapid wind-speed changes caused by atmospheric turbulence may be particularly detrimental because they produce short-term fluctuations in turbine output [25–27]. The ratio of the wind farm's installed capacity to the short-circuit power at the point of connection is also important: the greater the network short-circuit power, the lower the voltage sensitivity to changes in generation [28,29]. Permissible voltage deviations are specified in standards and by power-system operators [30].

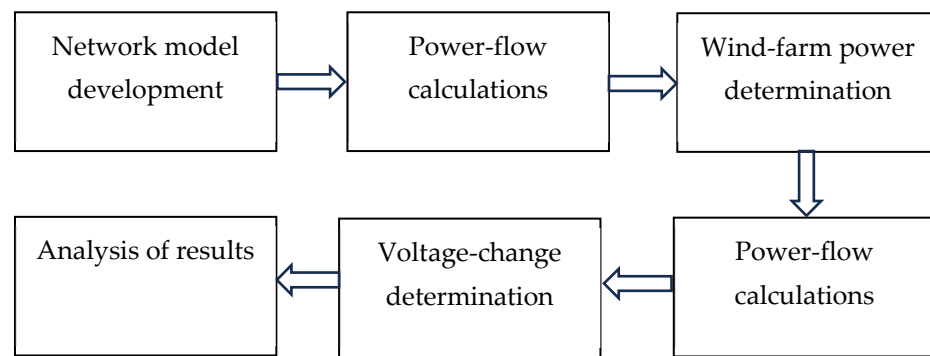
Despite the extensive literature on the effects of distributed generation on power network operation, comprehensive analyses that simultaneously consider the influence of wind-farm location and network load characteristics on voltage changes at individual nodes remain relatively limited. Previous studies have focused primarily on source capacity, generation level, voltage-control strategies or the optimisation of renewable-source connections, whereas the interaction between the source connection point and load parameters in determining the network voltage profile warrants further detailed investigation. Accordingly, this study addresses this gap by presenting simulation results on voltage changes in a medium-voltage network as a function of line loading and the wind-farm connection point.

## 2. Materials and Methods

### 2.1. Research Concept

The methodology was designed to isolate the effects of two principal factors: the source connection point and the nature of the line load unambiguously. Accordingly, the same network configuration and connection criterion were retained for all variants. In each case, the wind-farm power was selected so that connecting the source produced a 3% voltage rise at the point of connection. This approach enabled direct comparison of the effects of different source locations on the voltage profile along the entire line.

The adopted methodology was based on iterative power-flow calculations performed for successive wind-farm locations and different network-loading scenarios. For each case, the baseline network state was first determined, and the source power was adjusted until the voltage rise at the point of connection was exactly 3%. Once this condition was satisfied, a power-flow calculation was performed, and voltage changes were determined at every network node. The results were analysed to establish how source location and load characteristics affected the line voltage profile. Figure 1 presents a flowchart of the research methodology.



**Figure 1.** Flowchart of the research methodology.

The research procedure comprised the following steps:

1. Development of the MV network model in Digsilent PowerFactory.
2. Definition of the transformer, line and load parameters.
3. Determination of the baseline network state without wind-farm operation.
4. Connection of the wind farm at the node under analysis.
5. Selection of the source power required to produce a 3% voltage rise at the point of connection.
6. Power-flow calculation for the resulting operating state.
7. Determination of voltage changes at all network nodes.
8. Repetition of the procedure for successive source locations.
9. Repetition of the complete procedure for the different loading scenarios.
10. Analysis and comparison of the resulting voltage characteristics.

The adopted procedure enabled the assessment of both the local effect of the wind farm at the point of connection and its influence on the remaining sections of the network. The analysis employed conventional steady-state power-flow calculations. In each iteration, the voltage magnitudes and phase angles at all network nodes were determined from the following equations:

$$P_i = \sum_{j=1}^n U_i U_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \quad (2)$$

$$Q_i = \sum_{j=1}^n U_i U_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \quad (3)$$

where  $P_i$ ,  $Q_i$ —active and reactive powers at node  $i$  [W and VAR, respectively];  $U_i$ ,  $U_j$ —voltage magnitudes at nodes  $i$  and  $j$  [V];  $Y_{ij}$ —admittance between nodes  $i$  and  $j$  [S]; and  $\delta_i$ ,  $\delta_j$ —voltage phase angles at nodes  $i$  and  $j$  [rad].

These equations form the basis for the power-flow calculations used by power system operators in connection studies for renewable energy sources. The principal parameter

considered when assessing the effect of a source on the power network is the voltage change caused by wind-farm operation, defined as:

$$\Delta U = \frac{U_{WT} - U_0}{U_n} \cdot 100\% \quad (4)$$

where  $\Delta U$ —voltage change caused by wind-farm operation [%];  $U_{WT}$ —voltage after connection of the wind farm [V];  $U_0$ —line voltage before connection of the source [V]; and  $U_n$ —nominal line voltage [V].

Positive values of  $\Delta U$  denote a voltage rise caused by wind-farm operation, whereas negative values denote a voltage reduction. To ensure comparability, wind farms with a fixed rated power were not considered. Instead, the source power was selected individually for each connection point so that the voltage change at the point of connection was exactly 3%. This criterion reflects the approach commonly used in grid-connection studies and enables direct comparison of the effects of different source locations on the network voltage profile.

The study considered three network operating conditions:

1. An unloaded line;
2. A line with a resistive-inductive load; and
3. A line with a resistive-capacitive load.

For each condition, voltages at all network nodes were analysed for successive wind-farm locations. This enabled the effects of both the source connection point and the load characteristics on the network voltage distribution to be determined.

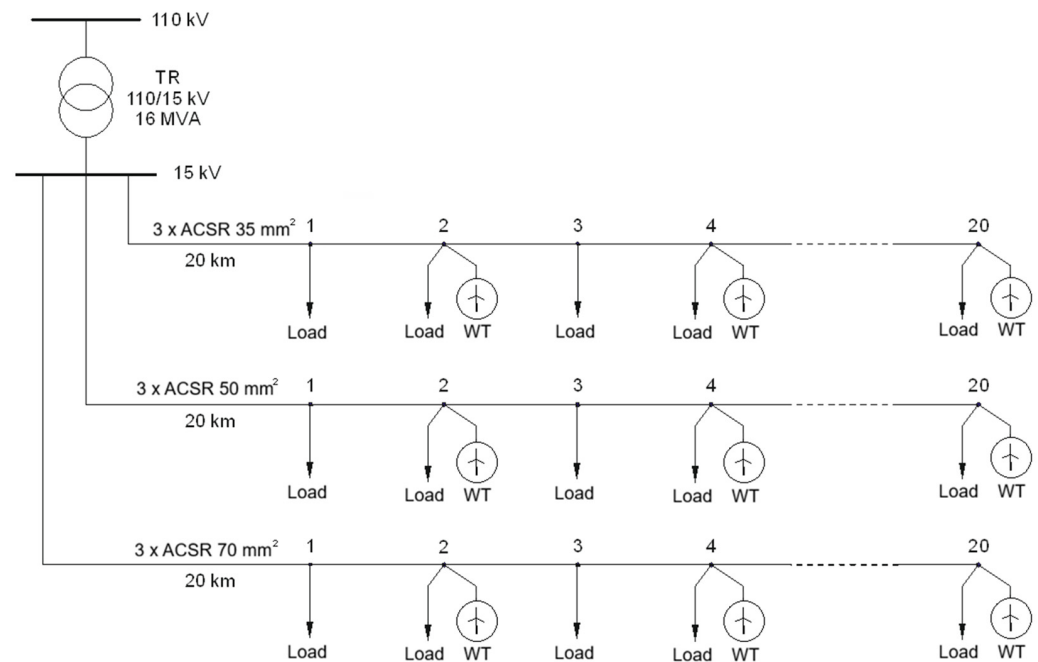
## 2.2. Description of the System Under Study

The study used a model of a medium-voltage power-network section developed in the DIGSILENT PowerFactory simulation environment (Figure 2). The model parameters were selected to represent, as closely as possible, the conditions found in actual MV distribution networks operated by distribution system operators. The analysed network was supplied from an HV/MV substation connected to the national power system at 110 kV. The short-circuit power at the connection point was set to 1000 MVA, representing a comparatively strong supply network. A 16 MVA HV/MV transformer was installed at the substation. Three radial MV overhead lines constructed using bare aluminium conductor steel-reinforced (ACSR) conductors extended from the substation. Each line was 20 km long. To assess the effect of line parameters, conductor cross-sections of 70, 50 and 35 mm<sup>2</sup> were considered. The different cross-sections enabled the influence of line impedance on voltage changes during generator operation to be assessed. Twenty loads were connected to each line at consecutive nodes spaced at 1 km intervals.

This configuration allowed voltage changes to be observed along the full length of each line and the effect of the source connection point on individual nodes to be evaluated. The network was analysed both without load and with each load consuming 100 kW of active power. The power factor was fixed at  $\cos \varphi = 0.95$ . Separate calculation series were performed for resistive-inductive and resistive-capacitive loads to determine the effect of load type on voltage distribution. The total load on each line was 2 MW. The wind farm was connected only at even-numbered nodes of the line under analysis. At each node, the wind-farm power was selected so that its operation caused a 3% change in voltage at the point of connection.

The model comprised a single 110/15 kV, 16 MVA transformer supplying three radial MV lines. At each MV node, only the net power consumed or generated was modelled; detailed information on MV/LV equipment was omitted to preserve the calculations' general applicability. The wind farm was modelled as an active-power source connected

to the network at different nodes. No specific turbine type or rated power was assumed, because the source power was selected separately for each scenario to produce a 3% voltage rise at the point of connection. To isolate the effect of source location on voltage conditions, voltage regulators and the turbine's reactive-power control systems were excluded. The load power factor was held constant at  $\cos \varphi = 0.95$  for both the resistive-inductive and resistive-capacitive cases. Consequently, the results reflect the effects of source location and load characteristics, without the additional influence of the control algorithms used in modern wind turbines.



**Figure 2.** Schematic diagram of the MV network model implemented in PowerFactory (TR—transformer; WT—wind turbine).

### 3. Results and Discussion

#### 3.1. Analysis of Voltage Changes Resulting from the Connection of a Wind Farm to an Unloaded Line

The first stage of the study analysed the network with no load at any node, a condition commonly considered in grid-connection studies to assess the hosting capacity of MV lines. The literature [8] identifies the minimum-load, maximum-generation scenario as critical for absolute voltage rise and reverse power flow. In the present study, the unloaded case also provided a reference for isolating the effect of source location. To examine more closely how voltage at individual network nodes varied with the wind-farm connection point, simulations were performed; the results are presented in Table 1.

Table 1 presents the voltage changes at individual nodes of an unloaded MV line constructed using a 35 mm<sup>2</sup> ACSR conductor, caused by a wind farm connected successively at even-numbered nodes from 2 to 20. In each case, the wind-farm power was selected individually so that the voltage rise at the point of connection was exactly 3%. This enabled a direct comparison of the effect of source location on the voltage profile along the entire line.

The results show that, for every wind-farm location considered, the voltage change at the point of connection was 3%, as prescribed by the calculation criterion. At all nodes downstream of the wind farm, towards the end of the line, the voltage rise also remained at 3%. For example, when the wind farm was connected at node 8, the voltage at nodes 8–20 increased by exactly 3%; when it was connected at node 14, the same rise was observed

at nodes 14–20. This behaviour results from the absence of loads on the line. In the unloaded section downstream of the connection point, no current flows, so no additional voltage drop occurs across the conductor impedance. Consequently, the entire section beyond the wind farm remains at essentially the same voltage. This finding is consistent with results reported by other authors [31,32].

**Table 1.** Voltage changes at individual nodes of an unloaded 35 mm<sup>2</sup> ACSR MV line caused by a wind farm connected at different nodes.

| Node Number      | Voltage Change Caused by Connecting the Wind Farm at the Node |       |       |       |       |       |       |       |       |       |
|------------------|---------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                  | 2                                                             | 4     | 6     | 8     | 10    | 12    | 14    | 16    | 18    | 20    |
| 15 kV substation | 0.097                                                         | 0.078 | 0.059 | 0.047 | 0.039 | 0.033 | 0.029 | 0.026 | 0.023 | 0.021 |
| 1                | 1.546                                                         | 0.807 | 0.548 | 0.415 | 0.334 | 0.280 | 0.240 | 0.211 | 0.188 | 0.169 |
| 2                | 3.000                                                         | 1.536 | 1.037 | 0.783 | 0.629 | 0.526 | 0.452 | 0.396 | 0.353 | 0.318 |
| 3                | 3.000                                                         | 2.268 | 1.527 | 1.152 | 0.925 | 0.773 | 0.664 | 0.582 | 0.518 | 0.466 |
| 4                | 3.000                                                         | 3.000 | 2.017 | 1.521 | 1.221 | 1.020 | 0.876 | 0.767 | 0.683 | 0.615 |
| 5                | 3.000                                                         | 3.000 | 2.508 | 1.890 | 1.517 | 1.267 | 1.088 | 0.953 | 0.848 | 0.764 |
| 6                | 3.000                                                         | 3.000 | 3.000 | 2.260 | 1.813 | 1.514 | 1.300 | 1.139 | 1.013 | 0.912 |
| 7                | 3.000                                                         | 3.000 | 3.000 | 2.630 | 2.110 | 1.761 | 1.512 | 1.324 | 1.178 | 1.061 |
| 8                | 3.000                                                         | 3.000 | 3.000 | 3.000 | 2.406 | 2.009 | 1.724 | 1.510 | 1.344 | 1.210 |
| 9                | 3.000                                                         | 3.000 | 3.000 | 3.000 | 2.703 | 2.256 | 1.937 | 1.696 | 1.509 | 1.359 |
| 10               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 2.504 | 2.149 | 1.882 | 1.674 | 1.508 |
| 11               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 2.752 | 2.362 | 2.068 | 1.840 | 1.657 |
| 12               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 2.574 | 2.254 | 2.005 | 1.806 |
| 13               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 2.787 | 2.441 | 2.171 | 1.955 |
| 14               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 2.627 | 2.337 | 2.104 |
| 15               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 2.813 | 2.502 | 2.253 |
| 16               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 2.668 | 2.403 |
| 17               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 2.834 | 2.552 |
| 18               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 2.701 |
| 19               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 2.851 |
| 20               | 3.000                                                         | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 | 3.000 |

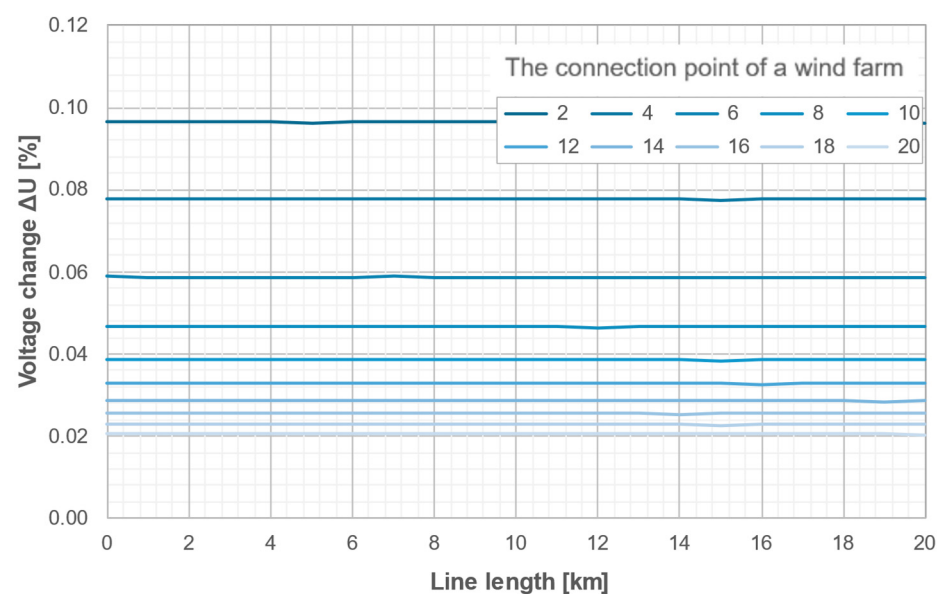
A different pattern occurs at nodes located between the HV/MV substation and the wind-farm connection point. Within this section, the influence of the source diminishes as it approaches the supply substation. The closer a node is to the substation, the smaller the observed voltage change is. For example, when the wind farm is connected at node 20, the voltage rise at the HV/MV substation is only 0.021%, whereas it reaches 2.851% at node 19 and the target value of 3% at node 20. The influence of the source on the voltage, therefore, progressively attenuates towards the supply node.

The results for the HV/MV substation are particularly noteworthy. The voltage rise at the substation decreases from 0.097% for a wind farm connected 2 km away to only 0.021% for a source connected 20 km away. This represents a more than four-fold reduction in the source's influence on voltage at the main supply point. The results confirm the substation's high-voltage stiffness and the limited effect of generation connected deep within the network on supply-side voltage conditions.

Analysis of successive nodes also reveals a clear relationship between a node's distance from the substation and its sensitivity to sources connected deeper within the network. When the wind farm is connected at node 20, the voltage changes are 0.615% at node 4, 1.210% at node 8, 1.806% at node 12 and 2.403% at node 16. Thus, node voltage sensitivity increases with distance from the HV/MV substation. The greater the line impedance between the substation and the node under consideration, the stronger the voltage effect of a source located farther downstream. This relationship is consistent with previous studies

showing that increased line impedance—primarily associated with line length—raises voltage sensitivity to distributed generation. Studies of voltage variation have shown that power injection from distributed sources causes voltage to rise along the line, with the effect becoming more pronounced with increasing distance from the supply point [32]. Analyses of actual MV networks similarly emphasise the importance of long lines and low loading in producing voltage rise, particularly deep within the network [33].

The literature [34,35] indicates that distributed generation may affect not only the voltage on the line to which it is connected, but also the voltages on adjacent lines through a common supply point or interline coupling. However, the magnitude of this interaction has not been quantified. The next stage of the study, therefore, determined the voltage changes caused by wind-farm operation on adjacent lines. Figure 3 shows the voltage change  $\Delta U$  on an unloaded parallel 50 mm<sup>2</sup> ACSR line caused by a wind farm connected to the 35 mm<sup>2</sup> ACSR line.



**Figure 3.** Voltage change along the parallel 50 mm<sup>2</sup> ACSR line caused by wind-farm operation for different wind-farm connection points on the 35 mm<sup>2</sup> ACSR line—unloaded condition.

The graph shows that the voltage change is practically independent of distance along the parallel line. All curves are almost horizontal, and the observed differences do not exceed a few thousandths of a percentage point. Within the analysed range, the distance from the HV/MV substation therefore has no material effect on the magnitude of the voltage rise. The wind-farm connection point has a much greater influence. As its distance from the HV/MV substation increases, the voltage change decreases systematically. For a connection point 2 km from the substation, the voltage change is approximately 0.096%, compared with approximately 0.020% for a connection point 20 km away. The largest voltage changes thus occur when the wind farm is connected near the beginning of the line; nevertheless, they remain small and do not exceed 0.1% of the supply voltage.

Similar results were obtained for the 70 mm<sup>2</sup> ACSR line. Thus, within the conditions considered, the conductor cross-section of the adjacent line does not affect the voltage changes produced by a wind farm connected to another MV line supplied from the same HV/MV substation.

### 3.2. Analysis of Voltage Changes Resulting from the Connection of a Wind Farm to a Line with a Resistive-Inductive Load

In the next stage, each load was assumed to consume 100 kW of active power at a lagging power factor of  $\cos \varphi = 0.95$ . Such a resistive-inductive load is representative of induction motors, which are widely used on farms and account for a substantial proportion of demand on rural feeders. The total line load was 2 MW. Table 2 presents the voltage changes caused by wind-farm operation as a function of the connection point and position along the 35 mm<sup>2</sup> ACSR line under a 2 MW resistive-inductive load.

**Table 2.** Voltage changes at individual nodes of a 35 mm<sup>2</sup> ACSR MV line caused by a wind farm connected at different nodes; line loaded to 2 MW at a lagging power factor of  $\cos \varphi = 0.95$  (resistive-inductive load).

| Node Number      | Voltage Change Caused by Connecting the Wind Farm at the Node |       |       |       |       |       |       |       |       |       |
|------------------|---------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                  | 2                                                             | 4     | 6     | 8     | 10    | 12    | 14    | 16    | 18    | 20    |
| 15 kV substation | 0.487                                                         | 0.310 | 0.235 | 0.193 | 0.165 | 0.145 | 0.129 | 0.117 | 0.106 | 0.097 |
| 1                | 1.743                                                         | 0.983 | 0.698 | 0.546 | 0.451 | 0.386 | 0.338 | 0.301 | 0.272 | 0.248 |
| 2                | 3.000                                                         | 1.656 | 1.159 | 0.899 | 0.737 | 0.627 | 0.547 | 0.486 | 0.438 | 0.399 |
| 3                | 3.026                                                         | 2.328 | 1.621 | 1.251 | 1.023 | 0.868 | 0.756 | 0.670 | 0.603 | 0.549 |
| 4                | 3.052                                                         | 3.000 | 2.082 | 1.603 | 1.308 | 1.108 | 0.964 | 0.854 | 0.768 | 0.699 |
| 5                | 3.076                                                         | 3.024 | 2.541 | 1.954 | 1.593 | 1.348 | 1.171 | 1.038 | 0.933 | 0.849 |
| 6                | 3.098                                                         | 3.046 | 3.000 | 2.304 | 1.876 | 1.587 | 1.378 | 1.220 | 1.097 | 0.998 |
| 7                | 3.119                                                         | 3.067 | 3.021 | 2.652 | 2.159 | 1.825 | 1.584 | 1.402 | 1.260 | 1.146 |
| 8                | 3.139                                                         | 3.086 | 3.040 | 3.000 | 2.441 | 2.062 | 1.790 | 1.584 | 1.423 | 1.294 |
| 9                | 3.157                                                         | 3.104 | 3.057 | 3.018 | 2.721 | 2.298 | 1.994 | 1.765 | 1.585 | 1.442 |
| 10               | 3.174                                                         | 3.121 | 3.074 | 3.034 | 3.000 | 2.534 | 2.198 | 1.944 | 1.747 | 1.588 |
| 11               | 3.189                                                         | 3.136 | 3.089 | 3.048 | 3.015 | 2.767 | 2.400 | 2.123 | 1.907 | 1.734 |
| 12               | 3.203                                                         | 3.149 | 3.102 | 3.062 | 3.028 | 3.000 | 2.601 | 2.301 | 2.067 | 1.879 |
| 13               | 3.215                                                         | 3.161 | 3.114 | 3.074 | 3.040 | 3.012 | 2.801 | 2.478 | 2.225 | 2.023 |
| 14               | 3.226                                                         | 3.172 | 3.125 | 3.084 | 3.050 | 3.022 | 3.000 | 2.653 | 2.382 | 2.166 |
| 15               | 3.235                                                         | 3.181 | 3.134 | 3.093 | 3.059 | 3.031 | 3.009 | 2.827 | 2.539 | 2.308 |
| 16               | 3.243                                                         | 3.189 | 3.141 | 3.101 | 3.066 | 3.038 | 3.016 | 3.000 | 2.694 | 2.449 |
| 17               | 3.249                                                         | 3.195 | 3.147 | 3.106 | 3.072 | 3.044 | 3.022 | 3.006 | 2.848 | 2.589 |
| 18               | 3.254                                                         | 3.200 | 3.152 | 3.111 | 3.077 | 3.048 | 3.026 | 3.010 | 3.000 | 2.727 |
| 19               | 3.257                                                         | 3.203 | 3.155 | 3.114 | 3.080 | 3.051 | 3.029 | 3.013 | 3.003 | 2.864 |
| 20               | 3.259                                                         | 3.204 | 3.157 | 3.116 | 3.081 | 3.053 | 3.031 | 3.015 | 3.004 | 3.000 |

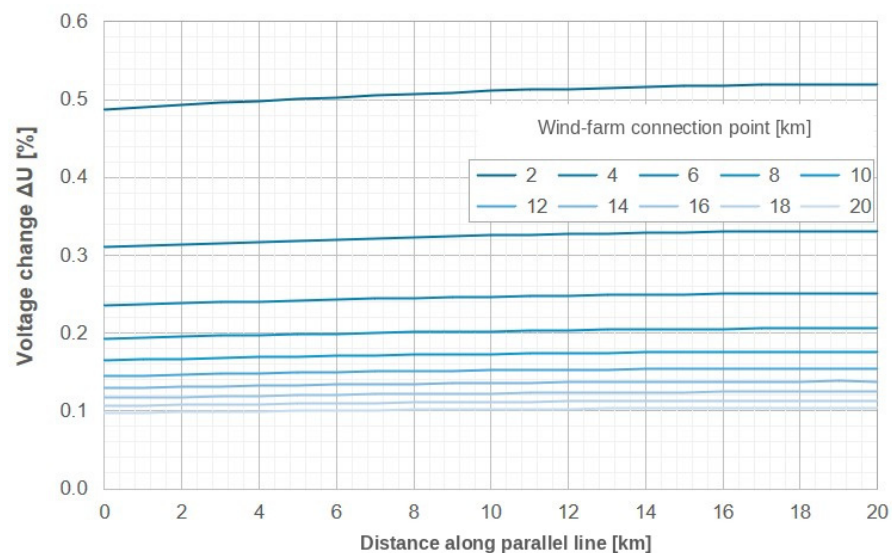
The results show that the presence of load substantially changes the voltage distribution. Unlike the unloaded line, there is no longer a downstream region in which the voltage change remains constant at 3%. In many cases, the voltage change continues to increase beyond the wind farm and exceeds the adopted threshold. For example, when the wind farm is connected at node 2, the voltage rise increases from 3% at the point of connection to 3.259% at the final node. The same behaviour occurs for all source locations considered.

The wind farm also has a markedly greater effect on the voltage at the HV/MV substation. Depending on source location, the substation voltage change ranges from 0.097% to 0.487%, compared with 0.021–0.097% for the unloaded line. Line loading, therefore, increases the source's influence on the wider power network. Voltage sensitivity to sources connected at different points also increases with the distance of the node under consideration from the substation. At the same time, the voltage-change pattern becomes more complex because the final voltage distribution depends not only on wind-farm location but also on the power flows between the source and the loads distributed along the line. Similar conclusions were reported by Akinyemi et al. [8] and Salimon et al. [10],

who showed that generator location may have a decisive influence on voltage levels and network hosting capacity.

Compared with the unloaded-line results (Table 1), the resistive-inductive load produces a clear increase in voltage changes throughout the network. For the unloaded line, the maximum voltage change did not exceed 3%, and a region of constant voltage occurred downstream of the connection point. For the loaded line, however, the maximum voltage changes range from approximately 3.05% to 3.26%, with the largest rises generally occurring deep within the network rather than at the wind-farm connection point. An assessment based solely on voltage at the point of connection may therefore underestimate the actual changes at other network nodes. A similar phenomenon was described by Walling et al. [3], who noted that conventional hosting-capacity methods based exclusively on local voltage changes may underestimate the actual effect of distributed generation on network operation. The present results consequently confirm that the complete line voltage profile must be considered when determining the maximum connectable wind-farm capacity, particularly in networks with a substantial proportion of resistive-inductive loads.

Figure 4 shows the voltage change  $\Delta U$  on the parallel 50 mm<sup>2</sup> ACSR line carrying a 2 MW resistive-inductive load, caused by a wind farm connected to the 35 mm<sup>2</sup> ACSR line.



**Figure 4.** Voltage change along the parallel 50 mm<sup>2</sup> ACSR line caused by wind-farm operation for different wind-farm connection points on the 35 mm<sup>2</sup> ACSR line; 2 MW load at a lagging power factor of  $\cos \varphi = 0.95$ .

In all scenarios shown in Figure 4, the voltage change increases slightly with distance along the line, and the curves follow a pattern similar to that observed on the source-connected line. The highest values occur when the wind farm is connected closest to the HV/MV substation (2 km), for which  $\Delta U$  increases from approximately 0.49% to 0.52%. As the source connection point moves farther from the substation, the voltage rise gradually decreases, reaching approximately 0.10–0.12% at the end of the line (20 km). The effect of the wind farm on the adjacent line is therefore measurable but substantially weaker than on the line directly connected to the source. Comparison with the unloaded condition shows that network loading amplifies the influence of both position along the line and source location on voltage change. Consequently, neglecting voltage changes on an adjacent loaded line may lead to an incomplete assessment of compliance with network voltage limits. As in the unloaded case, the voltage changes were effectively identical for adjacent conductors with cross-sections of 50 and 70 mm<sup>2</sup>.

### 3.3. Analysis of Voltage Changes Resulting from the Connection of a Wind Farm to a Line with a Resistive-Capacitive Load

A capacitive load is associated with electronic equipment used in both households and modern farms; for example, inverter-controlled machines may present a resistive-capacitive load. The next stage, therefore, examined voltage changes in an MV network carrying a 2 MW resistive-capacitive load, with the wind farm connected at selected nodes. The results are presented in Table 3.

**Table 3.** Voltage changes at individual nodes of a 35 mm<sup>2</sup> ACSR MV line caused by a wind farm connected at different nodes; line loaded to 2 MW at a leading power factor of  $\cos \varphi = 0.95$  (resistive-capacitive load).

| Node Number      | Voltage Change Caused by Connecting the Wind Farm at the Node |       |       |       |       |       |       |       |       |       |
|------------------|---------------------------------------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                  | 2                                                             | 4     | 6     | 8     | 10    | 12    | 14    | 16    | 18    | 20    |
| 15 kV substation | 0.461                                                         | 0.292 | 0.221 | 0.180 | 0.154 | 0.135 | 0.120 | 0.108 | 0.098 | 0.090 |
| 1                | 1.732                                                         | 0.973 | 0.689 | 0.539 | 0.445 | 0.381 | 0.333 | 0.296 | 0.267 | 0.243 |
| 2                | 3.000                                                         | 1.652 | 1.156 | 0.896 | 0.735 | 0.625 | 0.545 | 0.484 | 0.435 | 0.396 |
| 3                | 3.017                                                         | 2.327 | 1.620 | 1.251 | 1.024 | 0.869 | 0.756 | 0.670 | 0.603 | 0.548 |
| 4                | 3.034                                                         | 3.000 | 2.083 | 1.605 | 1.310 | 1.111 | 0.966 | 0.856 | 0.769 | 0.699 |
| 5                | 3.049                                                         | 3.015 | 2.542 | 1.956 | 1.596 | 1.351 | 1.174 | 1.040 | 0.935 | 0.849 |
| 6                | 3.063                                                         | 3.030 | 3.000 | 2.306 | 1.880 | 1.591 | 1.382 | 1.224 | 1.099 | 0.999 |
| 7                | 3.077                                                         | 3.043 | 3.013 | 2.654 | 2.162 | 1.829 | 1.588 | 1.406 | 1.263 | 1.147 |
| 8                | 3.089                                                         | 3.055 | 3.025 | 3.000 | 2.443 | 2.066 | 1.794 | 1.587 | 1.426 | 1.295 |
| 9                | 3.100                                                         | 3.066 | 3.036 | 3.011 | 2.722 | 2.302 | 1.998 | 1.768 | 1.587 | 1.442 |
| 10               | 3.110                                                         | 3.076 | 3.047 | 3.021 | 3.000 | 2.536 | 2.201 | 1.947 | 1.748 | 1.588 |
| 11               | 3.119                                                         | 3.086 | 3.056 | 3.030 | 3.009 | 2.769 | 2.402 | 2.125 | 1.908 | 1.733 |
| 12               | 3.128                                                         | 3.094 | 3.064 | 3.039 | 3.017 | 3.000 | 2.603 | 2.302 | 2.067 | 1.877 |
| 13               | 3.135                                                         | 3.101 | 3.072 | 3.046 | 3.025 | 3.007 | 2.802 | 2.478 | 2.225 | 2.021 |
| 14               | 3.142                                                         | 3.108 | 3.078 | 3.052 | 3.031 | 3.014 | 3.000 | 2.653 | 2.382 | 2.163 |
| 15               | 3.147                                                         | 3.113 | 3.083 | 3.058 | 3.036 | 3.019 | 3.005 | 2.827 | 2.538 | 2.305 |
| 16               | 3.152                                                         | 3.118 | 3.088 | 3.062 | 3.041 | 3.023 | 3.010 | 3.000 | 2.693 | 2.446 |
| 17               | 3.155                                                         | 3.122 | 3.092 | 3.066 | 3.044 | 3.027 | 3.013 | 3.004 | 2.847 | 2.586 |
| 18               | 3.158                                                         | 3.124 | 3.094 | 3.069 | 3.047 | 3.030 | 3.016 | 3.006 | 3.000 | 2.725 |
| 19               | 3.160                                                         | 3.126 | 3.096 | 3.070 | 3.049 | 3.031 | 3.018 | 3.008 | 3.002 | 2.863 |
| 20               | 3.161                                                         | 3.127 | 3.097 | 3.071 | 3.050 | 3.032 | 3.019 | 3.009 | 3.003 | 3.000 |

The results in Table 3 show that a resistive-capacitive load also produces a non-linear distribution of voltage changes throughout the network. As with the resistive-inductive load, the maximum values do not occur exclusively at the wind-farm connection point but also arise farther along the line. For example, when the source is connected at node 2, the voltage rise increases from 3.000% at the point of connection to 3.161% at the final node. This indicates that wind-farm operation reduces voltage drops when supplying power to loads distributed along the line.

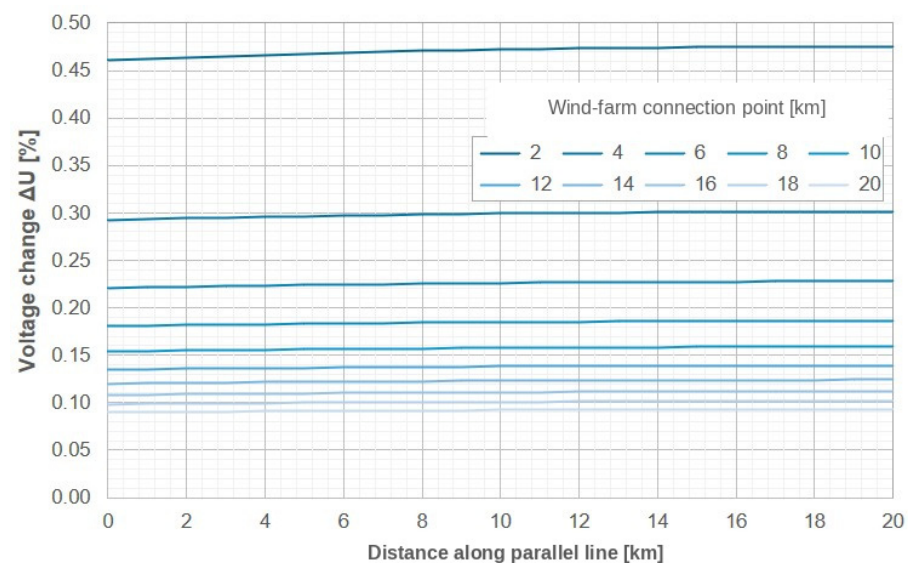
As in the preceding scenario, the source also has a measurable effect at the HV/MV substation. The substation voltage change ranges from 0.090% to 0.461%, with the largest values occurring for sources connected near the beginning of the line. As the connection point moves farther from the substation, the wind farm's effect on voltage at the main supply point progressively decreases.

A relationship is again evident between a node's distance from the substation and its sensitivity to wind-farm operation. Nodes deep within the network exhibit larger voltage changes than those located closer to the HV/MV substation. This confirms the important role of line impedance in shaping the voltage profile when distributed sources are operating.

Comparison with the resistive-inductive case (Table 2) shows that both load types produce very similar voltage distributions. However, the voltage rises are slightly smaller for the resistive-capacitive load. For example, when the wind farm is connected at node 2, the maximum voltage change is 3.161%, compared with 3.259% for the resistive-inductive load. Similar differences occur for the other source locations. This results from the capacitive load partially compensating for the effect of line reactance, thereby limiting voltage rise deep within the network.

Comparison with the unloaded-line results reveals a fundamental change in network behaviour. For the unloaded line, the downstream voltage rise at the connection point remained constant at 3%, and the maximum voltage change did not exceed the threshold. In the presence of a resistive-capacitive load, however, the maximum voltage changes exceed 3% and occur at nodes remote from the wind-farm connection point. As in the resistive-inductive case, an assessment based solely on voltage at the point of connection may therefore fail to represent the actual voltage changes elsewhere in the network.

Figure 5 presents the voltage change  $\Delta U$  as a function of distance along a parallel 50 mm<sup>2</sup> ACSR line carrying a 2 MW resistive-capacitive load, for various wind-farm connection points on the 35 mm<sup>2</sup> ACSR line. The curves are almost horizontal, indicating that distance along the parallel line has only a minor effect on voltage change: between 0 and 20 km, only a slight increase is observed. The values lie within a relatively narrow but still relevant range of approximately 0.10–0.47%.



**Figure 5.** Voltage change along the parallel 50 mm<sup>2</sup> ACSR line caused by wind-farm operation for different wind-farm connection points on the 35 mm<sup>2</sup> ACSR line; 2 MW load at a leading power factor of  $\cos \varphi = 0.95$ .

Comparison of the curves for the two load characteristics reveals differences in the magnitude of the voltage change. For the resistive-inductive load (Figure 4), the maximum values are approximately 0.50–0.52%, whereas for the resistive-capacitive load (Figure 5), they are approximately 0.46–0.48%. In both cases, the values are several times greater than for the unloaded line. The unloaded-line curves are almost entirely horizontal, indicating a negligible effect of distance along the line. For a loaded line, by contrast, voltage change increases slightly but distinctly with distance because line impedance and power flow become more influential. As in the previous case, increasing the conductor cross-section from 50 to 70 mm<sup>2</sup> produced no material difference in voltage change along the parallel line.

The present study focused on steady-state voltage changes calculated using conventional power-flow analysis, which serves as the basis for grid-connection studies assessing the integration of renewable energy sources into distribution networks. A simplified, balanced radial-network model and a constant wind-farm output—selected to produce a 3% voltage rise at the point of connection—were therefore adopted. This approach enabled the effects of source location and load characteristics on the network voltage profile to be evaluated unambiguously. Actual power networks, however, may have multi-branch structures, unbalanced phase loading, variable renewable generation and consumer demand, and modern wind turbines that actively control voltage and reactive power. Chronological time-series analyses, transient studies, network-monitoring and forecasting methods based on real-time parameter estimation, machine learning and graph neural networks are also becoming increasingly important. Although these issues lie beyond the scope of the present study, they constitute natural directions for further research into the effects of renewable sources on distribution-network operation.

#### 4. Conclusions

The simulation study enabled a detailed assessment of how wind-farm location and line-loading characteristics affect the voltage profile of MV distribution networks. The results show that, in radial networks, the greatest voltage deviations occur under loaded conditions. For the unloaded line, the voltage rise downstream of the wind farm remained at the 3% threshold, whereas the source's influence on nodes closer to the HV/MV substation decreased sharply, with values ranging from 0.021% to 0.097%. Generation connected deep within the network therefore causes only marginal voltage changes at the main supply point.

Markedly different characteristics were obtained for lines carrying a 2 MW load. For both resistive-inductive and resistive-capacitive loads, the voltage change profile was non-linear, with maximum values exceeding 3%. Notably, the largest deviations occurred not at the wind-farm connection point but farther downstream, owing to changes in power flow and reductions in local voltage drop. At a node 12 km from the HV/MV substation, the voltage rise reached approximately 3.2% when the wind farm was connected near the substation and then decreased as the source connection point moved farther away. For the capacitive load, the voltage change increased almost linearly along the line due to partial compensation of the line reactance. The analysis of adjacent lines further showed that, under loaded conditions, wind-farm operation may produce voltage changes of approximately 0.5%, which can be operationally significant for connected loads.

The following conclusions can be drawn from the study:

1. Wind-farm location significantly affects the voltage distribution throughout an MV network, and node voltage sensitivity increases with distance from the HV/MV substation.
2. For an unloaded line, the source mainly affects the section downstream of the point of connection, while its influence on the HV/MV substation remains small.
3. Network loading produces a non-linear distribution of voltage changes and may cause the largest voltage rises to occur deep within the network rather than at the wind-farm connection point.
4. Load characteristics affect the magnitude of voltage change; a resistive-capacitive load produces slightly smaller voltage rises than a resistive-inductive load.

The results demonstrate that wind-farm hosting capacity cannot be assessed solely from the voltage at the point of connection. In many cases, the 3% criterion is satisfied at the point of connection while the same threshold is exceeded elsewhere in the network. Comprehensive power-flow analysis, accounting for both load characteristics and line-

impedance parameters, is therefore required when planning the integration of renewable energy sources into MV networks.

Future work should extend the analysis to more complex network configurations, including multi-branch and meshed networks, and should account for the actual variability of wind generation and consumer demand. Another important research direction is the assessment of advanced voltage- and reactive-power-control systems for wind turbines and transformers equipped with on-load tap changers. Further studies should also consider the coordinated operation of different renewable sources and energy storage systems, as well as the application of artificial intelligence methods to monitor and forecast voltage conditions in distribution networks.

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