

Article

Factors and Effects of Harmonic Resonance in Medium-Voltage Distribution Networks with High Photovoltaic Penetration

Velichko Tsvetanov Atanasov ^{1,*}, Dimo Georgiev Stoilov ² , Nikolina Stefanova Petkova ³
and Elitsa Emilova Gieva ⁴ 

¹ Technical College of Sofia, Technical University of Sofia, 1000 Sofia, Bulgaria

² Faculty of Electrical Engineering, Technical University of Sofia, 1000 Sofia, Bulgaria; dstoilov@tu-sofia.bg

³ Faculty of Automatics, Technical University of Sofia, 1000 Sofia, Bulgaria; npetkova@tu-sofia.bg

⁴ Faculty of Electronic Engineering and Technologies, Technical University of Sofia, 1000 Sofia, Bulgaria; gieva@tu-sofia.bg

* Correspondence: vtcatanasov@tu-sofia.bg; Tel.: +359-889-231-201

Abstract

The increasing penetration of inverter-based renewable energy sources and the growing share of underground cable lines significantly modify the frequency-dependent characteristics of medium-voltage distribution networks, increasing the risk of harmonic resonance. Existing resonance studies are often based on detailed electromagnetic models that are difficult to apply during routine distribution network planning and operation. This paper proposes an engineering-oriented methodology for the preliminary assessment of harmonic resonance risk using an equivalent lumped-parameter model that incorporates overhead and cable lines, transformer inductance, photovoltaic generation, and the short-circuit strength of the supplying system. The methodology is applied to a representative 20 kV distribution network to investigate the influence of cable penetration, photovoltaic capacity, transformer loading, and grid strength on resonance conditions. The results show that increasing network capacitance and reducing short-circuit power shift the resonance frequency toward lower-order harmonics, increasing the probability of harmonic amplification. The highest resonance risk is observed under the combined conditions of high photovoltaic generation, low transformer loading, and weak-grid conditions. Unlike detailed electromagnetic simulation models, the proposed methodology enables rapid engineering assessment using parameters readily available to distribution system operators, thereby supporting network planning and operational decision-making in medium-voltage distribution systems with high photovoltaic penetration.

Keywords: harmonic resonance; medium-voltage distribution networks; photovoltaic generation; cable lines; short-circuit power; frequency domain analysis; power quality; engineering assessment



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1. Introduction

The rapid deployment of power electronic devices and renewable energy sources in power distribution networks leads to significant changes in their electrical characteristics and increases the importance of power-quality-related issues. Under conditions of rapidly growing integration of photovoltaic (PV) systems, wind power plants employing doubly-fed induction generators (DFIGs) and full-scale power electronic converters, uninterruptible power supplies (UPS), electric vehicle charging stations, as well as the widespread use of residential and commercial nonlinear loads (switched-mode power

supplies (SMPSs), inverter-based appliances, LED lighting systems, etc.), the level of harmonic distortion in the network increases considerably, creating favorable conditions for the occurrence of resonance phenomena in distribution systems [1–3]. Power systems may experience several types of resonance phenomena, including series resonance, parallel resonance, subsynchronous resonance, ferroresonance, and harmonic resonance [4]. While all of these resonance phenomena may adversely affect power system operation, harmonic resonance has become increasingly important in modern distribution networks due to the widespread penetration of renewable energy sources, inverter-based distributed generation, power electronic loads, and cable systems. It occurs as a result of the interaction between harmonic components generated by nonlinear loads and inverter-based sources and the frequency-dependent impedance of the electrical network. This phenomenon represents an interaction between the inductive and capacitive elements of the power system, where, at a specific frequency, conditions are created for significant amplification of harmonic voltages or currents. Such resonance conditions may lead to increased losses, local overheating of equipment, accelerated insulation ageing, and maloperation of protection systems in substations [5,6]. In distribution networks, the risk of harmonic resonance has increased due to several modern development trends, including the growing share of cable lines, the high penetration of inverter-based generation, and the presence of long distribution feeders. Cable lines introduce significant shunt capacitance, while overhead lines and transformers form the dominant inductive component of the network impedance. In addition, power electronic converters generate harmonic components over a wide frequency range, thus creating favorable conditions for resonance processes [7,8]. A characteristic feature of the Bulgarian electricity distribution system is the widespread use of 20 kV medium-voltage feeders operated by the country's distribution system operators. The distribution network is characterized by a combined structure of overhead and cable lines, together with an increasing penetration of distributed generation, particularly photovoltaic systems. According to the Bulgarian Energy and Water Regulatory Commission (EWRC), the installed photovoltaic capacity in Bulgaria has increased significantly in recent years [9], leading to substantial modification of the equivalent network parameters, especially through increased network capacitance and altered impedance frequency characteristics. Another important aspect is that photovoltaic systems typically generate maximum power during periods of relatively low network loading, such as midday hours, resulting in reverse power flow, changes in network operating conditions, and additional modification of the frequency-dependent network impedance. As a consequence, the resonance frequency may shift toward lower values, approaching the dominant harmonic components generated by inverter-based converters, particularly in the region of the fifth and seventh harmonics. Under such conditions, the probability of local amplification of harmonic voltages and currents increases significantly, creating a serious risk for the reliable operation of the distribution network. In many European countries and worldwide, transmission and distribution networks are operated by different system operators [10]. Nevertheless, harmonic phenomena exhibit a systemic nature and cannot be considered independently, as they propagate throughout the entire power system and across the interfaces between different voltage levels [11,12]. Distribution networks are particularly sensitive to harmonic resonance due to the high density of nonlinear loads, the increasing share of cable lines, and the widespread deployment of decentralized inverter-based generation sources [13–15]. Although resonance phenomena have been widely investigated in the scientific literature, a substantial part of existing studies focuses mainly on transmission systems or relies on complex simulation models that are difficult to apply in the practical operation of distribution system operators. Furthermore, there is often a lack of quantitative analysis regarding the influence of key factors such as line length and type, installed photovoltaic capacity,

and transformer parameters on resonance conditions. In engineering practice, there is a need for sufficiently accurate and practically applicable methods that enable rapid risk assessment based on available operational data.

This paper presents an investigation of resonance conditions in power distribution networks, with emphasis on the specific characteristics of the Bulgarian power system. A frequency-dependent equivalent model of the distribution network, based on lumped inductive and capacitive parameters, is developed to enable analytical assessment of the resonance frequency and the influence of the main network factors. The proposed model is supported by operational characteristics and typical parameters obtained from real 20 kV distribution networks, thereby increasing its engineering relevance and practical applicability. An analysis is performed for different network configurations and photovoltaic generation levels, and practically applicable engineering conclusions are formulated. Unlike many previously published studies, which mainly rely on detailed electromagnetic simulations or converter-specific models, the proposed approach introduces an integrated analytical frequency-dependent equivalent model intended for practical engineering assessment of harmonic resonance in medium-voltage distribution networks. The model simultaneously considers the combined influence of overhead and cable lines, photovoltaic generation, transformer parameters, and grid short-circuit power within a unified analytical framework. In addition, the proposed methodology enables rapid evaluation of resonance-frequency variations under different operating conditions using readily available network parameters, making it suitable for engineering applications related to distribution network planning and operation. This enables distribution system operators to perform preliminary resonance screening without the need for detailed electromagnetic simulation models or extensive converter-specific data. The proposed approach is intended not to replace detailed electromagnetic simulations, but to provide a computationally efficient engineering tool for preliminary resonance assessment and decision support during the planning and operation of modern distribution networks.

The main scientific contributions of this study are as follows:

- Development of an engineering-oriented methodology for assessing the influence of characteristic distribution network factors on harmonic resonance conditions.
- Development of an integrated frequency-dependent equivalent L–C model for engineering assessment of harmonic resonance in real medium-voltage distribution networks.
- Quantitative assessment of the sensitivity of the resonance frequency to variations in photovoltaic penetration, cable-line length, and grid short-circuit power.
- Integration of experimentally determined shunt conductance and no-load loss parameters of 20 kV overhead lines into the proposed frequency-dependent resonance model.
- Identification of operating conditions leading to increased harmonic resonance risk in medium-voltage distribution networks.
- Demonstration of the applicability of the proposed model as a practical decision-support tool for planning and operation of medium-voltage distribution networks.

2. Literature Review

Problems associated with harmonics and resonance phenomena in power systems are well recognized both in regulatory frameworks and in the scientific literature. IEEE Std 519-2022 [16] establishes recommendations and requirements for limiting harmonic distortion at the point of common coupling, while EN 50160 [17] defines the principal voltage characteristics in public distribution networks, including the permissible limits for harmonic voltages. These standards demonstrate that harmonic conditions are not merely a theoretical issue but are directly related to power quality and the reliable operation of electrical networks. With the increasing penetration of power-electronically

interfaced sources and loads, research efforts increasingly consider resonance as a result of the interaction between the frequency-dependent network impedance and the harmonic emissions of converters. In this context, impedance-based methods have become widely established, as they enable the identification of resonance frequencies, stability assessment, and analysis of possible harmonic amplification mechanisms. A comparative analysis of different resonance assessment methods for power electronics-dominated systems is presented by Sowa et al. [18]. The authors demonstrate that the impedance-based approach is particularly effective for identifying resonance frequencies and analyzing interactions between converters and network impedance. Similar conclusions are reported in more recent review studies on predictive impedance-based stability assessment, which emphasize the strong potential of these methods for practical application in converter-dominated networks. In addition to purely analytical approaches, recent years have also seen the development of methods for monitoring and assessing resonance conditions in real power systems. Ansari et al. [19] propose methods for optimal placement of power quality monitors in distribution networks in order to observe potential harmonic resonance conditions, with particular emphasis on harmonic resonance mode analysis. This demonstrates that modern research is no longer limited to offline simulations but increasingly seeks practical tools for monitoring and early detection of critical operating conditions. In the same direction, the review by Kervyn De Meerendre et al. [20] on local grid impedance estimation techniques highlights that the identification of resonance frequencies through impedance assessment is essential for the design of filters, compensation devices, and power quality improvement measures. A significant portion of contemporary research is dedicated to renewable energy sources, particularly systems involving wind turbines and DFIG-based converters. In such systems, the interaction between converters, cable sections, and the equivalent network impedance may lead to resonance phenomena over a wide frequency range. Zhang et al. [21] demonstrate that resonances ranging from several hertz to several kilohertz may occur in DFIG-based offshore wind farms, with both the resonance frequency and amplification level being strongly dependent on network topology and converter control strategies. Ghanavati et al. [22] further emphasize that impedance modeling and transfer function approaches are essential for evaluating harmonic and interharmonic interactions in DFIG systems. Huang et al. [23] additionally show that neglecting certain coupling mechanisms in the model, such as the influence of DC-link coupling, may result in inaccurate assessment of the frequency-dependent system behavior. The high penetration of photovoltaic systems and other power electronic loads has also been extensively investigated, although often in the context of general harmonic emission, harmonic mitigation, or hosting capacity analysis rather than through equivalent analytical models for resonance assessment in real distribution networks. More recent studies have examined the influence of cable sections and local network conditions on the emissions of string inverters, demonstrating that cable length can significantly affect the frequency response and filtering characteristics of the system. Other studies focus on network impedance reconstruction and mitigation of high-frequency resonances in cable distribution systems, further confirming the importance of line parameters for resonance conditions. Despite this considerable progress, several important limitations can still be identified in the literature. First, a large portion of the existing studies focuses on transmission systems, offshore wind farms, HVDC links, or highly detailed converter models, which limits their direct applicability in practical distribution system operation. Second, many of the proposed methods require detailed converter control parameters, high-resolution measurements, or sophisticated simulation environments. Third, relatively few studies provide simplified yet sufficiently accurate models capable of enabling rapid engineering assessment of the influence of line length and type, cable penetration level, installed PV capacity, and transformer parame-

ters on the resonance frequency [24]. Furthermore, only a limited number of published studies simultaneously consider the combined influence of overhead lines, cable sections, photovoltaic penetration, transformer parameters, and grid short-circuit power within a unified analytical framework suitable for practical engineering applications. Therefore, there is a clearly justified need for the development of analytical and practically applicable models for harmonic resonance assessment in medium-voltage distribution networks, particularly under conditions of mixed overhead and cable line structures and increasing penetration of decentralized generation sources. The present study is directed precisely toward this objective by employing an analytical L–C equivalent model for quantitative assessment of resonance conditions using parameters representative of real distribution networks [25]. Unlike many of the aforementioned studies, which rely on highly detailed frequency-dependent models and complex converter control representations, the present work proposes an analytical approach focused on engineering applicability and practical assessment of resonance conditions in real medium-voltage distribution networks.

3. Methodology and Modeling Approach

To investigate the conditions for harmonic resonance in medium-voltage distribution networks, a frequency-dependent analytical approach is adopted. The proposed methodology is based on the development of an equivalent network model using lumped inductive and capacitive parameters representative of real distribution systems. The model is intended to provide a balance between physical accuracy and engineering applicability, allowing rapid assessment of the influence of network configuration, cable penetration, photovoltaic generation, and short-circuit power on resonance conditions. The methodology includes the derivation of the equivalent network parameters, formulation of the resonance conditions, and frequency-domain analysis under different operating scenarios representative of real 20 kV distribution networks. The proposed approach follows a structured sequence consisting of equivalent network parameter determination, analytical formulation of the resonance conditions, evaluation of the frequency-dependent network characteristics, and engineering interpretation of the obtained results for practical distribution system applications.

3.1. Equivalent Model of the Distribution Network

The analysis of harmonic resonance in power distribution networks requires the use of a model that simultaneously reflects the main physical processes and remains suitable for practical engineering application. In the present study, a frequency-dependent equivalent model of the distribution network based on lumped parameters is developed. The considered distribution feeder is represented by an equivalent π -configuration consisting of a series branch and shunt branches connected to ground. The series branch includes the resistance (R) and inductance (L), representing, respectively, the active losses in the conductors and the inductive properties of the overhead lines, cable sections, and supplying transformer. The shunt branches include the equivalent capacitance (C_{line}), representing the line-to-ground capacitance of both overhead and cable lines, as well as the conductance (G), accounting for dielectric losses and leakage currents under real operating conditions.

Figure 1 presents the extended π -equivalent model of the investigated distribution feeder, including the main series and shunt parameters together with the equivalent representation of the connected photovoltaic systems.

3.2. Determination of Model Parameters

The accuracy of the proposed frequency-dependent model depends on the correct determination of the equivalent electrical parameters of the network components. In this

study, the model parameters are derived from the physical characteristics of the overhead lines, cable sections, transformers, and photovoltaic generation units. The following subsections describe the adopted parameter determination approach for each component of the distribution network.

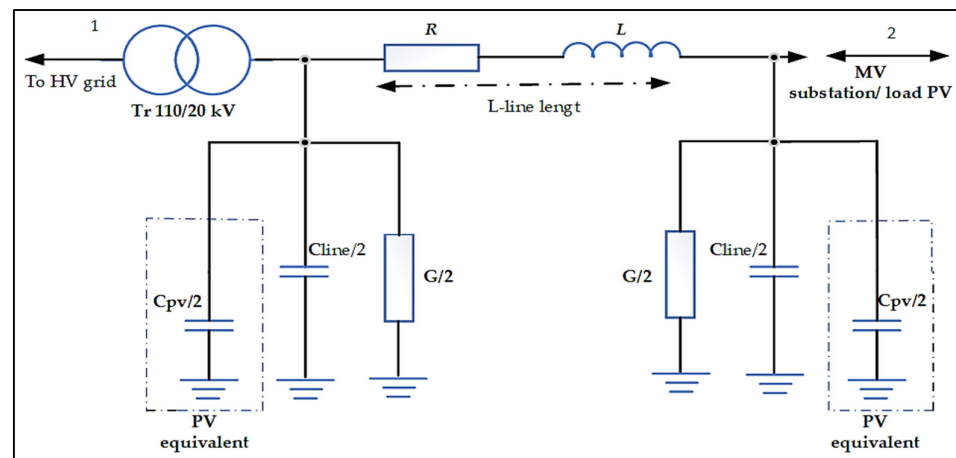


Figure 1. Extended π -equivalent model of a distribution line including series resistance, shunt capacitance, and the influence of photovoltaic systems.

3.2.1. Shunt Line Parameters: Capacitance and Conductance

In conventional engineering approaches, the shunt parameters of medium-voltage overhead lines are often assumed to be negligible. Although this assumption is acceptable for analyses dominated by longitudinal electrical processes, it is not fully justified in the investigation of harmonic and resonance phenomena, where shunt parameters play a significant role. The equivalent capacitance represents one of the key parameters governing the frequency-dependent behavior of the distribution network. As the proportion of underground cable sections increases, the total equivalent capacitance rises significantly, thereby modifying the network impedance characteristics and increasing the likelihood of harmonic resonance. Consequently, accurate estimation of the equivalent capacitance is essential for reliable engineering assessment of resonance-sensitive operating conditions. The equivalent capacitance of the distribution line can be represented as the sum of the capacitances of the overhead and cable sections:

$$C_{line} = C'_{ohl} \cdot l_{ohl} + C'_{cab} \cdot l_{cab} \quad (1)$$

where:

C'_{ohl} and C'_{cab} are the capacitances per unit length of the overhead and cable lines, respectively, while l_{ohl} and l_{cab} represent their corresponding lengths.

Figure 2 presents the equivalent capacitive model of the distribution network, including the main shunt parameters of the line. The line is represented by an equivalent line-to-ground capacitance C_{line} , symmetrically distributed as $C_{line}/2$ at both ends of the π -model. The capacitance C_{line} includes the combined contribution of the overhead and cable sections of the distribution feeder. At node 2, an equivalent capacitance C_{pv} is introduced to represent the influence of photovoltaic systems and their power electronic interfaces. The corresponding capacitive susceptance is determined by the following relationship:

$$B_c = \omega C \quad (2)$$

This relationship allows the equivalent susceptance of the system to be represented as the sum of the individual capacitive components. An increase in C_{line} and C_{pv} leads to an increase in the total network capacitance and consequently to a shift in the resonance

frequency. Although the capacitance of overhead lines is significantly lower than that of cable lines, its cumulative contribution cannot be neglected for long line lengths. This is particularly characteristic of medium-voltage distribution networks, where overhead feeders often extend over several tens of kilometers. In addition to capacitance, shunt conductance is also of considerable importance, as it accounts for dielectric losses and leakage currents under real operating conditions. In a previous study by the authors [26], based on experimental measurements performed on 20 kV overhead distribution lines, measurable shunt losses under no-load operating conditions were identified, mainly caused by leakage currents across insulators and the influence of atmospheric conditions. The obtained results indicate that under conditions of increased humidity and insulator contamination, shunt losses may reach values of up to 0.4–0.5 kW/km, demonstrating that shunt parameters cannot be considered negligible. It was also established that the total annual shunt losses may reach approximately 0.2–0.3% of the transmitted electrical energy, further confirming the significance of shunt-related processes in real distribution networks. These results justify the inclusion of a shunt branch in the equivalent model of the distribution line. The equivalent shunt conductance can be estimated using the following relationship:

$$G = \frac{P_{\text{idle}}}{U^2} \quad (3)$$

where:

P_{idle} represents the measured no-load losses and U is the nominal voltage.

For the representative 20 kV overhead lines considered in this study, the experimentally measured no-load losses reported in [26] correspond to equivalent shunt conductance values that were directly used in the equivalent network model. Rather than assuming an ideal lossless shunt branch, the proposed model incorporates these measured conductance values to represent the damping effect caused by leakage currents under real operating conditions.

Consequently, the proposed approach improves the engineering accuracy of the resonance analysis while maintaining the simplicity of the equivalent network model.

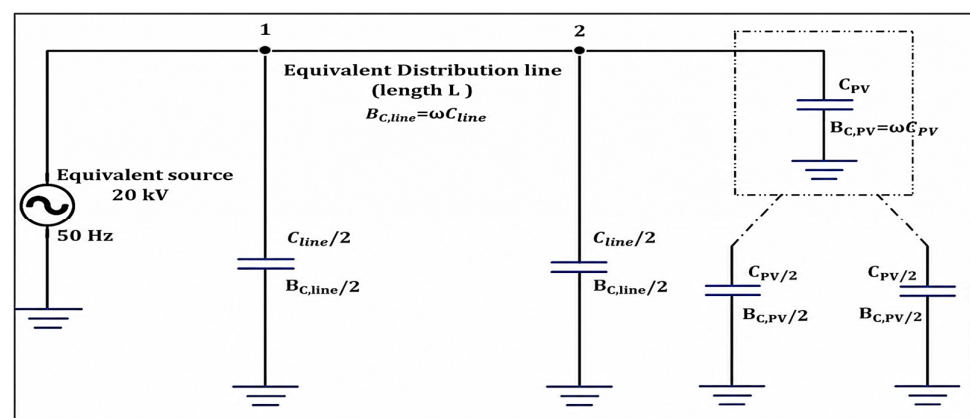


Figure 2. Equivalent capacitive representation of the distribution line, including line capacitance and photovoltaic-related capacitance.

The values presented in Table 1 indicate that cable lines are characterized by significantly higher capacitance per unit length than overhead lines. Nevertheless, for long overhead feeders, the cumulative capacitive contribution becomes substantial and cannot be neglected. In addition, photovoltaic inverters influence the frequency-dependent network impedance through their input capacitors, filters, and power electronic control systems. Depending on the operating conditions and frequency range, their behavior may exhibit both capacitive and inductive characteristics [27]. In the present study, the

analysis is restricted to steady-state operating conditions and the low-order harmonic range, for which the equivalent capacitive behavior is assumed to be dominant. Therefore, the influence of the photovoltaic inverters is represented by an equivalent capacitive component, which provides a simplified but sufficiently accurate engineering representation for preliminary resonance assessment in medium-voltage distribution networks. The equivalent capacitance C_{pv} does not represent the physical capacitance of a specific photovoltaic inverter or manufacturer-specific data. Instead, it is an equivalent engineering parameter representing the aggregated frequency-dependent capacitive behavior of inverter-based generation, including the combined influence of DC-link capacitors, EMI filters, LCL filters, and converter input admittance. The adopted values were selected to represent typical medium-voltage distribution feeders with increasing photovoltaic penetration and were used exclusively for comparative parametric analysis of resonance-frequency variations.

Table 1. Typical capacitance and capacitive susceptance of key components in MV distribution networks (50 Hz).

Component	Symbol	Typical Capacitance (C)	Capacitive Susceptance (Bc)
Overhead line (20 kV)	C_{ohl}	0.008–0.012 $\mu\text{F}/\text{km}$	2.5–3.8 $\mu\text{S}/\text{km}$
Cable line (20 kV)	C_{cab}	0.20–0.30 $\mu\text{F}/\text{km}$	63–94 $\mu\text{S}/\text{km}$
PV inverters (DC-link, filters)	C_{pv}	equipment-dependent	$BC_{pv} = \omega C_{pv}$

3.2.2. Series Line Parameters: Resistance and Inductance

The series parameters of the distribution line include the conductor resistance and the line inductance. The active resistance (R) determines the active power losses in the feeder and mainly influences the damping of resonance processes associated with current flow in the line, while the inductance (L) defines the inductive component of the network impedance. The equivalent series inductance plays a decisive role in determining the resonance frequency because it directly interacts with the equivalent network capacitance. Consequently, accurate estimation of the inductive parameters is essential for reliable frequency-domain analysis and engineering assessment of resonance conditions. The equivalent series inductance can be expressed as:

$$L = L_{\text{line}} \cdot l + L_{tr} \quad (4)$$

where:

L_{line} is the inductance per unit length of the line, l is the feeder length, and L_{tr} is the equivalent inductance of the supplying transformer. The active resistance has a limited influence on the resonance frequency itself; however, it significantly affects the damping of resonance processes and the amplitude of harmonic voltages and currents. At lower resistance values, the resonance is less damped, resulting in greater amplification of harmonic components. Therefore, both the inductive parameters and the damping effect associated with the series resistance should be considered when evaluating the resonance behavior of practical distribution networks.

Figure 3 presents the equivalent circuit of the distribution line, representing the main inductive components of the network. The supplying substation is modeled by an equivalent Thevenin source with impedance.

$$Z_s = R_s + j\omega L_s \quad (5)$$

This represents the combined influence of the transmission system and the 110/20 kV supplying transformer. The main feeder is represented by a series connection of inductances

corresponding to the overhead line sections L_{ohl} and cable sections L_{cab} , which form the dominant inductive component of the network impedance. Along the feeder, equivalent inductances $L_{tr,i}$ are included to represent the influence of the connected distribution transformers. An additional influence is exerted by the loading conditions of the distribution transformers. During periods of high photovoltaic generation and relatively low demand, which are typical for daytime operation, transformers often operate under low loading conditions. This results in reduced active damping of the resonance circuits and creates more favorable conditions for amplification of harmonic components [28,29]. Conversely, under higher evening loading conditions, the active component of the equivalent network impedance increases, leading to stronger damping of resonance processes and limitation of harmonic voltage and current amplitudes [30]. The equivalent parameters of the connected distribution transformers are represented as local shunt branches, since they modify the frequency-dependent impedance at the corresponding feeder nodes. For the purposes of the present analysis, their influence is taken into account through an equivalent inductive component $L_{tr,eq}$, determined on the basis of the equivalent inductances of the individual transformers and their locations along the feeder. The total equivalent inductance of the considered network can be estimated as follows:

$$L_{eq} = L_{ohl} + L_{cab} + L_{tr,eq} \quad (6)$$

where:

L_{ohl} and L_{cab} are the equivalent inductances of the overhead and cable sections, respectively, while $L_{tr,eq}$ represents the combined influence of the connected distribution transformers. In practical engineering assessment, $L_{tr,eq}$ can be determined from the equivalent transformer reactance calculated on the basis of the short-circuit voltage, rated power, and connection location within the network configuration. The presented equivalent circuit demonstrates that the resonance conditions are determined by the interaction between the equivalent inductive components of the lines, transformers, and supplying system, on the one hand, and the shunt capacitive parameters of the cable lines, overhead feeders, and inverter-based generation sources, on the other hand.

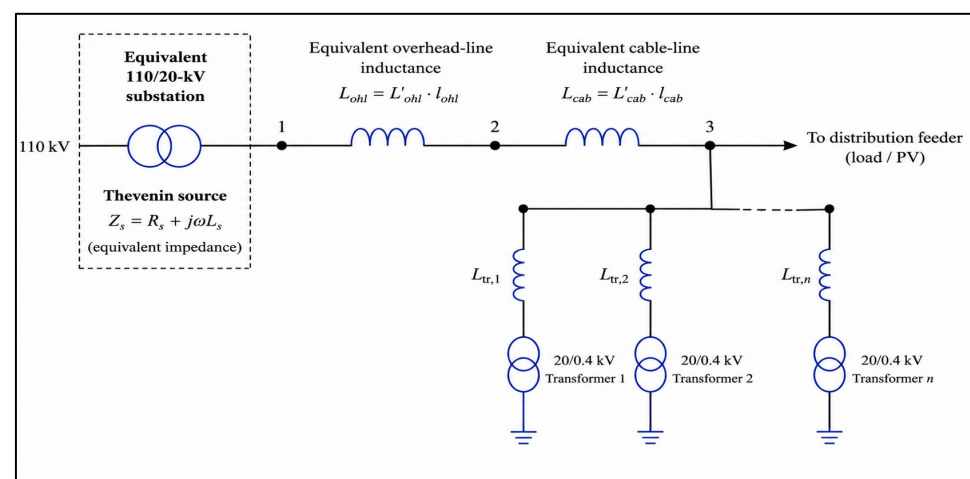


Figure 3. General equivalent network model adopted for the proposed resonance-analysis methodology.

3.2.3. Modeling of the Supplying Substation (Node 1)

The supplying substation, represented as node 1 in Figure 1, is considered as a source with finite short-circuit power, meaning that it does not behave as an ideal infinitely stiff voltage source. The supplying substation has a significant influence on the frequency-dependent characteristics of the distribution network and on the conditions for resonance

occurrence. Under real operating conditions, the substation possesses a finite internal impedance determined by the parameters of the transmission system, the supplying transformer, and the length of the connected transmission lines. Consequently, under certain operating conditions, the network may be characterized as a weak grid, which corresponds to relatively low short-circuit power and increased equivalent impedance. In the literature, the ratio between the short-circuit apparent power of the supplying network and the rated apparent power of the connected inverter-based generation, commonly referred to as the Short-Circuit Ratio (SCR), is frequently used as an indicator of grid strength:

$$SCR = \frac{S_{sc}}{S_{pv}} \quad (7)$$

where:

S_{sc} is the short-circuit power at the considered node, while S_{pv} is the rated apparent power of the connected photovoltaic generation sources. A typical classification of grid strength according to the SCR value is presented in Table 2. Since modern grid-connected photovoltaic inverters normally operate at a power factor close to unity during normal operation, the rated apparent power of the photovoltaic installation may be assumed approximately equal to its rated active power. Therefore, in the illustrative example, the value of $S_{pv} = 10$ MVA is considered equivalent to a rated active power of 10 MW.

Table 2. Typical qualitative classification of grid strength according to SCR.

SCR Value	Grid Strength	Typical Characteristics
$SCR > 5$	Strong grid	Stable voltage and low harmonic sensitivity
$SCR = 3\text{--}5$	Moderate grid	Increased sensitivity to harmonics and voltage variations
$SCR < 3$	Weak grid	High sensitivity to resonance and inverter interaction

For example, for a 20 kV distribution substation with a short-circuit power of $S_{sc} = 30$ MVA and connected photovoltaic generation with a rated active power of 10 MW (corresponding to an equivalent apparent power of $S_{pv} = 10$ MVA under the unity power-factor assumption), the following value is obtained:

$$SCR = \frac{30}{10} = 3.$$

According to the adopted classification in Table 2, this value corresponds to the lower boundary of the moderate-grid range and indicates operating conditions close to weak-grid behavior. Under such conditions, even relatively small variations in load or in the operating conditions of the connected generation sources may lead to significant changes in voltage levels and the frequency-dependent characteristics of the network. Such conditions are typical for long distribution feeders located far from the main supplying substations, as well as for networks with a high concentration of decentralized photovoltaic generation. In these cases, the combination of increased network capacitance and relatively high network impedance creates favorable conditions for the occurrence of harmonic resonance. In weak grids, the resonance frequency may shift toward lower-order harmonics, thereby increasing the probability of interaction with the characteristic harmonics generated by power electronic converters [31].

3.3. Conditions for Resonance Occurrence

Harmonic resonance occurs when the inductive and capacitive reactances become equal:

$$X_l = X_c \quad (8)$$

Under these conditions, the network impedance reaches its maximum value in the case of parallel resonance, leading to amplification of harmonic voltages and currents. The resonance frequency depends on the equivalent inductive and capacitive parameters of the network and can be determined as follows:

$$f_r = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}} \quad (9)$$

The above relationship shows that an increase in the equivalent capacitance C_{eq} , as well as in the equivalent inductance L_{eq} , leads to a reduction in the resonance frequency. In real distribution networks, this effect may be observed under the following conditions:

- **Increase in cable line length.**

In recent years, distribution networks have shown a clear trend toward increasing the share and length of cable lines, particularly in urban areas and during the reconstruction of existing feeders. The main reasons for this include higher reliability requirements, reduction in right-of-way corridors, improved performance under adverse weather conditions, and easier integration of new consumers and decentralized generation sources [32]. The increase in cable line length leads to higher equivalent shunt capacitance and consequently to a decrease in the resonance frequency.

- **Presence of long overhead lines.**

Long overhead feeders have a significant influence on resonance conditions in distribution networks. In engineering practice, it is often assumed that the economically justified length of overhead lines is of the same order as the nominal network voltage level (for example, approximately 20–30 km for 20 kV networks). However, under real operating conditions, particularly in sparsely populated or mountainous regions, the length of distribution feeders may considerably exceed these values and in some cases reach 80–100 km [33]. Increasing the length of overhead lines simultaneously increases both the equivalent inductance and the shunt capacitance to ground, thereby substantially modifying the frequency-dependent characteristics of the network and the resonance conditions.

- **Integration of photovoltaic systems and inverter-based converters.**

Despite the development of modern power quality standards and the significant progress achieved in power electronics and inverter technologies, problems associated with harmonic distortion and resonance phenomena remain highly relevant. One of the main reasons is the widespread deployment of inverter-based devices and power electronic converters, which, despite their high efficiency and advanced control systems, still generate harmonic components in the network [34]. Furthermore, the input capacitors, filters, and power electronic interfaces of the converters influence the frequency-dependent impedance of the network. Depending on the operating conditions and frequency range, their behavior may exhibit both capacitive and inductive characteristics; however, under the considered operating conditions, the increase in the equivalent shunt capacitance of the system is dominant.

- **Influence of the short-circuit power of the supplying substation.**

At low short-circuit power levels, the equivalent network impedance increases and the system becomes more sensitive to harmonic disturbances. Under such conditions, even relatively small harmonic currents generated by inverter-based sources may produce significant harmonic voltages. The increased network impedance intensifies the frequency-dependent interactions between the network and the power electronic converters, thereby increasing the probability of resonance occurrence and harmonic amplification [35].

- **Influence of the loading conditions of distribution transformers.**

During periods of high photovoltaic generation and relatively low local demand, transformers and consumer loads provide a weaker damping effect on harmonic components. Under such operating conditions, the active damping of the network decreases, creating more favorable conditions for amplification of harmonic voltages and interaction with the resonance frequencies of the network [36]. Under the combined influence of the above-mentioned factors, the resonance frequency may shift toward lower values and approach the dominant harmonic components generated by inverter-based sources, most commonly in the region of the fifth and seventh harmonics. This creates conditions for local amplification of harmonic voltages and currents, increased losses, overheating of equipment, and maloperation of protection systems.

3.4. Main Assumptions of the Model

The proposed methodology is based on a frequency-dependent equivalent representation of the distribution network and includes both network parameters and operating conditions affecting harmonic resonance behavior.

Figure 4 presents the methodological framework of the proposed frequency-dependent approach for harmonic resonance analysis in distribution networks. The scheme summarizes the main network parameters, operating conditions, and stages of the equivalent modeling and frequency-domain analysis used for the assessment of resonance conditions and the network sensitivity to harmonic disturbances. The proposed methodology combines both structural network characteristics and operational conditions affecting the frequency-dependent behavior of the distribution system. The network model includes the influence of overhead and cable line lengths, transformer equivalent parameters, short-circuit power, and the contribution of inverter-based sources. In parallel, the operating regime accounts for photovoltaic generation levels, inverter influence, load conditions, and the possibility of reverse power flow during periods of high PV generation and low local consumption. Based on these input parameters, an equivalent frequency-dependent network model is developed and subsequently used for resonance-frequency assessment and harmonic sensitivity analysis. The obtained results allow the evaluation of resonance-frequency displacement, harmonic amplification risk, and possible mitigation measures under different operating scenarios representative of modern distribution networks with high penetration of inverter-based generation. The following main assumptions were adopted in the development of the equivalent model:

- The distribution network is represented by lumped parameters selected to reproduce the principal frequency-dependent characteristics of the real network within the considered harmonic analysis range;
- The system is analyzed under steady-state operating conditions, while transient electromagnetic processes are not considered;
- For the purposes of harmonic analysis, the parameters of the network elements are assumed to be independent of the instantaneous voltage and current values within the considered frequency range;
- The control systems and internal algorithms of the power electronic converters are not modeled in detail, and their influence is represented through equivalent parameters;
- Equivalent network parameters suitable for engineering assessment of resonance conditions are employed;
- The influence of higher-order harmonics outside the considered frequency range is assumed to be limited and is therefore not analyzed in detail;
- The adopted assumptions enable the development of a frequency-dependent equivalent model suitable for engineering assessment of harmonic and resonance phenomena in real power distribution networks.

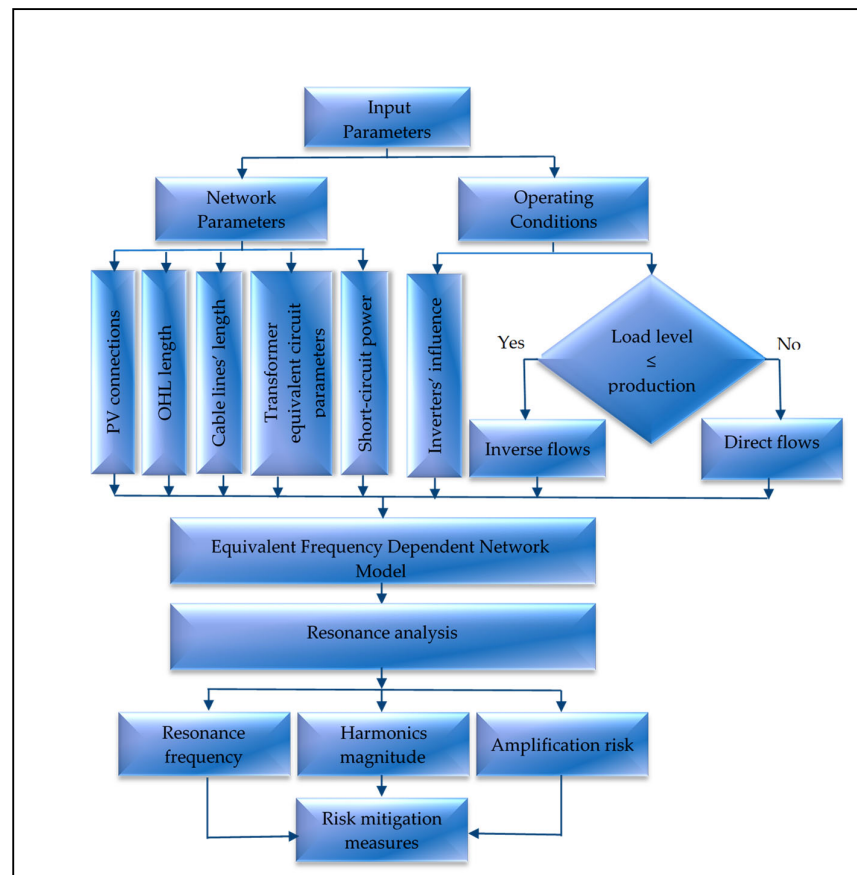


Figure 4. Methodological framework of the proposed frequency-dependent resonance assessment approach for distribution networks with photovoltaic generation.

4. Frequency-Domain Analysis and Discussion

After determining the equivalent parameters of the distribution network, a frequency-domain analysis of the system was performed in order to evaluate the variation in the resonance conditions under different network configurations and operating modes. The analysis was based on the equivalent L–C model presented in the previous sections, with particular focus on the influence of:

- The length of overhead lines;
- The length of cable sections;
- The installed capacity of connected photovoltaic systems;
- The short-circuit power of the supplying substation;
- The loading conditions of the distribution transformers.

The analysis demonstrated that an increase in the equivalent network capacitance caused by cable lines and photovoltaic systems, as well as an increase in the equivalent inductance associated with long overhead feeders and low short-circuit power, leads to a shift of the resonance region toward lower frequencies. The most unfavorable operating conditions were observed under the combined presence of:

- High photovoltaic generation;
- Low daytime loading conditions;
- Long distribution feeders;
- Low short-circuit power.

Under such operating conditions, the resonance frequency may approach the region of the eighth and ninth harmonic orders, thereby increasing the probability of local ampli-

cation of harmonic voltages and currents. Unlike simplified resonance models assuming negligible shunt losses, the present model incorporates experimentally determined shunt conductance, resulting in a more realistic representation of resonance damping in medium-voltage overhead distribution networks.

4.1. Case Study: Typical 20 kV Distribution Feeder

For the purposes of the frequency-domain analysis, a representative 20 kV medium-voltage distribution feeder was considered. The network configuration and the adopted parameters are based on typical characteristics of real distribution feeders operated by Bulgarian distribution system operators but do not correspond to a single identified feeder.

Figure 5 presents the simplified equivalent representation of the investigated 20 kV distribution feeder used for the frequency-domain analysis. The feeder includes a long overhead-line section, a cable section, connected distribution transformers, and distributed photovoltaic generation sources supplied from a 110/20 kV primary substation. The presented configuration reflects typical operating conditions of real medium-voltage distribution networks with mixed overhead and cable structures. The selected case study was designed to represent typical engineering conditions encountered in practical medium-voltage distribution systems. This allows the proposed methodology to be evaluated under representative operating conditions while maintaining sufficient generality for application to similar distribution networks. The considered feeder includes a 40 km overhead line and a 5 km cable section. The network is supplied by a 110/20 kV substation with a short-circuit power of 80 MVA. The main parameters of the investigated network are presented in Table 3. In the base-case analysis presented in Table 4, the resonance frequency is calculated using the equivalent feeder inductance L_{feeder} . The influence of the supplying system, including the 110/20 kV transformer and the upstream network, is represented separately by the equivalent source inductance L_s and is introduced in the weak-grid analysis presented in Section 4.3. Therefore, the equivalent source inductance is not included in the numerical calculations of the base case but is introduced separately in the weak-grid analysis. Photovoltaic systems with a total installed capacity of up to 3 MW are connected along the feeder.

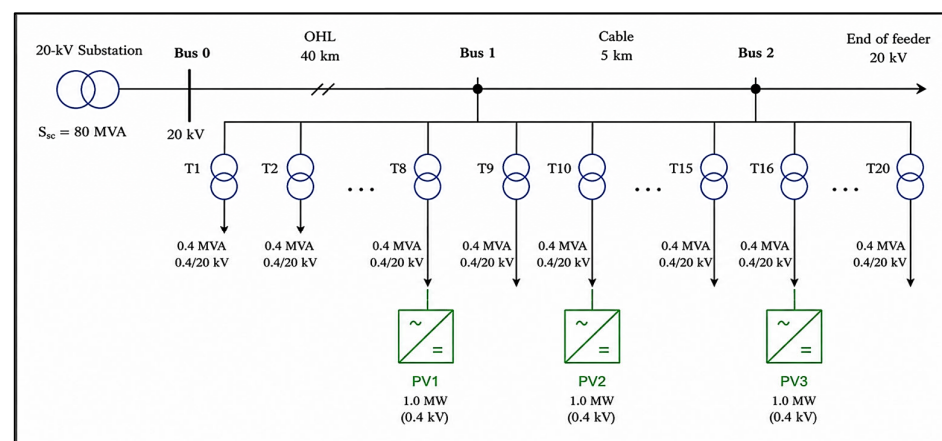


Figure 5. Frequency-dependent equivalent model of the representative 20 kV distribution feeder used for the numerical analysis.

The equivalent shunt conductance used in the numerical analysis was calculated from the experimentally determined no-load losses reported in [26] and was equal to 0.52 mS/km (520 μ S/km). This parameter was kept constant throughout the investigated operating scenarios because the objective of the parametric analysis was to evaluate the influence of cable length, photovoltaic penetration, and grid short-circuit strength. The experimentally

determined conductance provides realistic damping of the equivalent resonance circuit and therefore improves the engineering representativeness of the obtained results. The equivalent inductance of the overhead line section is given by:

$$L_{OHL} = L'_{OHL} \cdot l_{OHL} = 1.05 \times 40 = 42 \text{ mH}$$

Table 3. Main parameters of the investigated 20 kV distribution feeder.

Parameter	Symbol	Value
Nominal voltage	U_n	20 kV
Overhead line length	l_{ohl}	40 km
Cable line length	l_{cab}	5 km
OHL inductance	L'_{ohl}	1.05 mH/km
Cable inductance	L'_{cab}	0.35 mH/km
OHL capacitance	C'_{ohl}	0.01 μ F/km
Cable capacitance	C'_{cab}	0.20 μ F/km
Short-circuit power	S_{sc}	80 MVA
PV power scenarios	P_{pv}	0; 0.5; 1.0; 2.0; 3.0 MW
Network frequency	f	50 Hz

Table 4. Effect of PV penetration on equivalent capacitance and resonance frequency.

Case	P_{pv} MW	C_{pv} μ F	C_{eq} μ F	f_r Hz	Harmonic Order
Base case	0	0.00	1.40	643	12.9
Low PV	0.5	0.05	1.45	632	12.6
Moderate PV	1.0	0.10	1.50	621	12.4
High PV	2.0	0.20	1.60	602	12.0
Critical PV	3.0	0.30	1.70	584	11.7

The inductance of the cable section is determined as follows:

$$L_{CAB} = L'_{CAB} \cdot l_{CAB} = 0.35 \times 5 = 1.75 \text{ mH}$$

Consequently, the equivalent inductance of the distribution feeder can be expressed as:

$$L_{feeder} = L_{OHL} + L_{CAB} = 43.75 \text{ mH}$$

For the subsequent weak-grid analysis, the equivalent inductance used in the resonance calculations is obtained as the sum of the feeder inductance and the equivalent source inductance associated with the supplying substation. The feeder inductance remains constant for all investigated scenarios, whereas the equivalent source inductance varies as a function of the available short-circuit power. The capacitance of the overhead line is determined as follows:

$$C_{OHL} = C'_{OHL} \cdot l_{OHL} = 0.01 \times 40 = 0.40 \text{ } \mu\text{F}$$

The capacitance of the cable section is given by:

$$C_{CAB} = C'_{CAB} \cdot l_{CAB} = 0.20 \times 5 = 1 \text{ } \mu\text{F}$$

The base equivalent capacitance without photovoltaic systems is determined as follows:

$$C_{eq,0} = C_{OHL} + C_{CAB} = 1.40 \text{ } \mu\text{F}$$

For engineering assessment of the resonance conditions, several operating scenarios were considered, as presented in Table 4.

To account for the influence of photovoltaic inverters, an equivalent additional capacitance C_{pv} was introduced, increasing proportionally with the level of connected photovoltaic generation capacity. It should be noted that the adopted values of the equivalent capacitance C_{pv} represent an engineering approximation of the combined frequency-dependent effect of photovoltaic inverters, including the influence of DC-link capacitors, EMI filters, LCL filters, and the equivalent input admittance of the power electronic converters. The selected values are intended to reflect typical operating conditions of medium-voltage distribution networks with different levels of connected photovoltaic generation and are consistent with the impedance-based equivalent modeling approaches commonly adopted in the literature for converter-interfaced power systems [13,20,36]. It should be emphasized that the parameter C_{pv} does not represent the physical capacitance of a specific photovoltaic inverter or manufacturer-specific data. Instead, it is introduced as an equivalent engineering parameter describing the aggregated frequency-dependent capacitive behavior of the connected photovoltaic generation. The values presented in Table 4 were selected to represent increasing levels of aggregated photovoltaic penetration in a typical 20 kV distribution feeder and are intended for comparative parametric analysis of resonance-frequency variations rather than for reproducing the internal design of a particular inverter. The objective of the study is to evaluate the sensitivity of the resonance frequency to increasing photovoltaic penetration using a simplified engineering-oriented equivalent model. Depending on the operating conditions and frequency range, photovoltaic inverters may exhibit both capacitive and inductive characteristics. In the present study, their influence is represented by an equivalent capacitive component because this behavior is dominant within the investigated frequency range and has the greatest influence on the displacement of the resonance frequency. This corresponds to a shift from the region of the 13th harmonic toward the region between the 11th and 12th harmonics. The obtained results demonstrate that even under realistic photovoltaic penetration levels for a 20 kV distribution feeder, inverter-based generation sources may have a substantial influence on resonance conditions. The risk further increases in the presence of longer cable sections, lower short-circuit power, or low daytime loading conditions, when the active damping of resonance processes becomes less pronounced. In order to evaluate the possibility of shifting the resonance frequency toward lower harmonic orders, the following sections investigate the influence of cable-line length and the short-circuit power of the supplying substation. These factors may lead to a further displacement of the resonance region toward lower harmonic orders. From an engineering perspective, the obtained relationships indicate that resonance-sensitive operating conditions may occur even under moderate photovoltaic penetration levels when combined with long feeders and weak-grid conditions. Therefore, frequency-dependent assessment of the network impedance becomes increasingly important during the planning of new photovoltaic installations and the reconstruction of existing distribution feeders.

Figure 6 illustrates the relationship between the operating conditions of the distribution network and the variation in the resonance frequency. The resonance frequency was calculated according to the relationship presented in Equation (9), while varying the equivalent network capacitance as a function of the photovoltaic generation level, whereas the equivalent inductance of the considered feeder was kept constant.

During daytime operation, the increase in photovoltaic generation under relatively low network loading conditions leads to reduced equivalent damping and enhanced capacitive influence within the system. As a result, the resonance frequency shifts toward lower values and reaches a minimum around midday, when photovoltaic generation is at its max-

imum and local consumption remains relatively low. The analysis demonstrates a clearly pronounced tendency for the resonance frequency to decrease with increasing connected photovoltaic capacity. The obtained relationships indicate that under conditions of high photovoltaic generation and low daytime loading, the resonance frequency approaches the range of characteristic harmonic components generated by inverter-based converters. This increases the probability of local amplification of harmonic voltages and currents within the distribution network. These results demonstrate that photovoltaic penetration alone may significantly modify the resonance characteristics of medium-voltage distribution networks, even without changes in the physical network configuration.

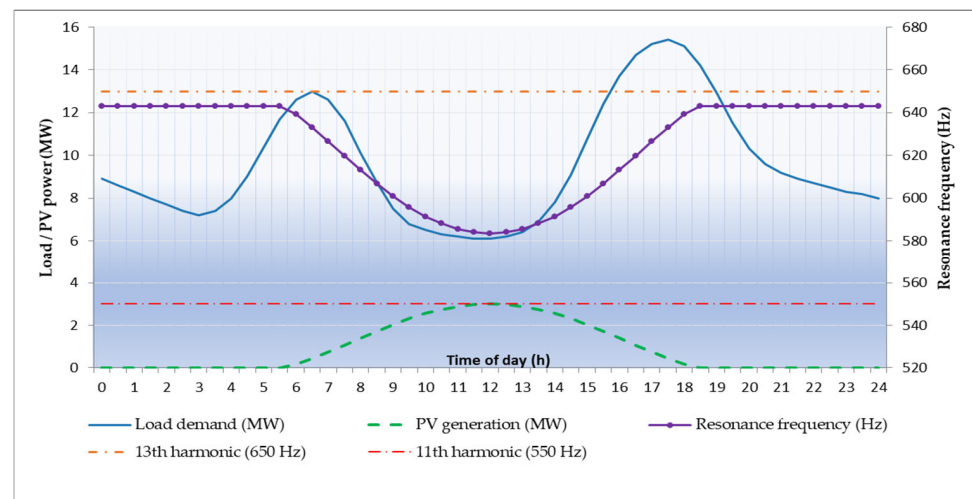


Figure 6. Influence of photovoltaic generation on the resonance frequency under representative daily loading conditions of the analyzed 20 kV distribution feeder.

4.2. Influence of Cable Length

The length of cable lines has a significant influence on the frequency-dependent characteristics of the distribution network due to their substantially higher capacitance compared to overhead lines. Increasing the share of cable sections leads to an increase in the equivalent shunt capacitance of the network and consequently to a reduction in the resonance frequency. In order to evaluate this effect, a parametric analysis was performed for different cable section lengths while all other network parameters were kept unchanged. The analysis was carried out using a base photovoltaic generation capacity of $P_{pv} = 1$ MW and a short-circuit power of the supplying substation of $S_{sc} = 80$ MVA. For the purpose of isolating the capacitive effect of increasing cable penetration, the equivalent feeder inductance was kept constant, while only the equivalent shunt capacitance was varied according to the investigated cable-line length. This approach makes it possible to exclusively evaluate the influence of cable-line capacitance on the resonance frequency without interference from changes in other network parameters. The adopted assumptions provide a consistent basis for comparing different cable penetration scenarios and assessing their impact on harmonic resonance conditions. The calculated resonance frequencies for the investigated cable-line lengths are summarized in Table 5.

The obtained results demonstrate a clearly pronounced decrease in the resonance frequency with increasing cable line length. For a relatively short cable section of 1 km, the resonance frequency is approximately 909 Hz, corresponding roughly to the 18th harmonic order. When the cable section length is increased to 10 km, the resonance frequency decreases to approximately 481 Hz, corresponding to the region between the 9th and 10th harmonic orders. The analysis confirms that cable-line length is one of the dominant

parameters governing the resonance frequency, emphasizing the importance of considering cable penetration during network planning and reconstruction.

Table 5. Influence of cable-line length on resonance frequency.

Cable Length (km)	Equivalent Capacitance (μF)	Resonance Frequency (Hz)	Harmonic
1	0.70	909	18.2
3	1.10	725	14.5
5	1.50	621	12.4
8	2.10	525	10.5
10	2.50	481	9.6

4.3. Influence of Weak-Grid Conditions

The short-circuit power of the supplying substation has a significant influence on the frequency-dependent characteristics of the distribution network. A reduction in short-circuit power leads to an increase in the equivalent network impedance and to higher sensitivity to harmonic disturbances and resonance phenomena. In order to evaluate this effect, a parametric analysis was performed for different values of the short-circuit power of the supplying substation. During the analysis, the parameters of the distribution feeder and the connected photovoltaic generation capacity of $P_{PV} = 1$ MW were kept unchanged. For each investigated short-circuit power level, the equivalent source inductance was adjusted while the feeder inductance and the equivalent capacitance remained unchanged. The total inductive parameter used in the resonance analysis therefore reflects the combined influence of the distribution feeder and the supplying network. The resonance frequency for each operating scenario was calculated using Equation (9), where the total equivalent inductance is obtained from the sum of the feeder inductance and the equivalent source inductance. For comparative purposes, a relative resonance amplification index K_{amp} was introduced. This index expresses the relative increase in the equivalent source impedance under weak-grid conditions with respect to the base case. Assuming the same harmonic current injection, the resulting harmonic voltage amplification is approximately proportional to the equivalent network impedance. Therefore, the relative amplification index can be estimated as:

$$K_{amp} = \frac{Z_{s,i}}{Z_{s,ref}} \approx \frac{S_{sc,ref}}{S_{sc,i}} \quad (10)$$

where:

$S_{sc,ref}$ is the short-circuit power of the reference case and $S_{sc,i}$ is the short-circuit power of the investigated weak-grid scenario. In this study, the case with $S_{sc} = 80$ MVA is used as the reference condition. The equivalent source impedance was calculated from the three-phase short-circuit power at the 20 kV bus using:

$$Z_s = \frac{U_n^2}{S_{sc}} \quad (11)$$

The corresponding equivalent source inductance is determined as:

$$L_s = \frac{Z_s}{2\pi f} = \frac{U_n^2}{2\pi f S_{sc}} \quad (12)$$

where

$U_n = 20$ kV and $f = 50$ Hz. Consequently, the total inductance used in the resonance analysis is determined as:

$$L_{total} = L_{feeder} + L_s \quad (13)$$

The calculated resonance frequencies and the corresponding resonance amplification indices obtained for different short-circuit power levels are summarized in Table 6.

Table 6. Influence of short-circuit power on resonance conditions.

S_{sc} (MVA)	Equivalent Source Inductance L_s (mH)	Total Equivalent Inductance L_{total} (mH)	Resonance Frequency (Hz)	Harmonic Order	Relative Resonance Amplification Index K_{amp}
80	15.92	59.67	532	10.6	1.00
50	25.46	69.21	494	9.9	1.60
30	42.44	86.19	443	8.9	2.67

The obtained results demonstrate that a reduction in short-circuit power increases the equivalent source inductance of the supplying system. Consequently, the total equivalent inductance used in the resonance model increases, resulting in a progressive decrease in the resonance frequency. In the considered case study, the resonance frequency decreases from approximately 532 Hz at $S_{sc} = 80$ MVA to approximately 443 Hz at $S_{sc} = 30$ MVA, corresponding to a shift in the equivalent harmonic order from approximately 10.6 to 8.9. In addition to the shift in resonance frequency, the relative resonance amplification index increases from 1.00 to 2.67. In weaker grids, the equivalent network impedance is higher, resulting in higher harmonic voltages for the same injected harmonic currents. These findings confirm that the short-circuit power of the supplying substation is a key parameter governing both the resonance frequency and the susceptibility of the distribution network to harmonic amplification.

4.4. Combined Effect of PV and Weak Grid

The combined influence of high photovoltaic generation and weak-grid conditions is of particular importance for the occurrence of harmonic resonance. Under real operating conditions, these factors frequently act simultaneously, especially in long distribution feeders with a high concentration of inverter-based generation sources and limited short-circuit power. In order to evaluate the combined effect, a parametric analysis was performed for different values of connected photovoltaic generation capacity and different short-circuit power levels of the supplying substation. During the analysis, the cable section length was kept constant at $l_{cab} = 5$ km, while the remaining network parameters corresponded to the base case presented in Section 4.1. The obtained results demonstrate a clearly pronounced nonlinear interaction between the capacitive effect of photovoltaic systems and the inductive characteristics of weak supplying networks. A simultaneous increase in PV generation capacity and reduction in short-circuit power leads to a substantial shift in the resonance frequency toward lower values. The analysis indicates that in a relatively strong network $S_{sc} = 80$ MVA, the influence of PV generation on the resonance frequency remains limited, and the resonance region remains approximately within the range of the 11th to 13th harmonics. However, when the short-circuit power is reduced to 50 MVA and 30 MVA, a significantly stronger shift of the resonance frequency toward lower values is observed. Under the most unfavorable operating conditions considered, corresponding to $S_{sc} = 30$ MVA and $P_{PV} = 3$ MW, the resonance frequency decreases to approximately 416 Hz, corresponding to an equivalent harmonic order of approximately 8.3 and therefore to the region between the eighth and ninth harmonics. This demonstrates that the combined effect of weak-grid conditions and high inverter-based generation can substantially modify the frequency-dependent characteristics of the distribution network. The practical significance of this result is particularly important for modern distribution networks with an increasing share of cable lines and inverter-based generation sources.

The obtained relationships indicate the necessity of taking into account the frequency-dependent characteristics of the network when integrating new photovoltaic generation capacities, reconstructing distribution feeders, and evaluating the operating conditions of weak grids. The combined influence of weak-grid conditions and photovoltaic penetration results in a significantly stronger resonance-frequency shift than the effect of each factor considered separately, demonstrating the necessity of simultaneous evaluation of these parameters during engineering planning and network assessment.

4.5. Practical Interpretation and Engineering Implications

The obtained results demonstrate that the increasing penetration of inverter-based renewable energy sources substantially modifies the frequency-dependent characteristics of modern distribution networks. In mixed overhead-cable distribution feeders, the combined influence of cable capacitance, photovoltaic systems, and weak-grid conditions may lead to a significant shift in the resonance frequency toward lower values. From an engineering perspective, the obtained results indicate that resonance phenomena should be taken into account not only in transmission systems but also in the planning and operation of medium-voltage distribution networks. Particular attention is required for long distribution feeders with a high concentration of photovoltaic generation and limited short-circuit power, where the probability of harmonic amplification is considerably higher. The proposed frequency-domain approach may support distribution system operators in identifying resonance-sensitive operating conditions, evaluating the impact of photovoltaic integration and increasing cable penetration, and supporting engineering decisions related to the planning and operation of modern medium-voltage distribution networks. Based on these findings, several practical recommendations can be formulated for distribution system planning and operation. Before integrating large photovoltaic power plants or extending underground cable sections, a frequency-dependent impedance assessment should be performed to identify possible resonance frequencies. Particular attention should be paid to long mixed overhead-cable feeders, where the cumulative cable capacitance may significantly reduce the resonance frequency. For feeders supplied from weak grids (low short-circuit power), harmonic studies are recommended before commissioning new converter-based generation, since these operating conditions considerably increase the probability of harmonic amplification. Where resonance risk is identified, mitigation measures such as passive or active harmonic filters, optimization of inverter control parameters, active damping techniques, or network reconfiguration should be considered. Finally, harmonic measurements should be carried out after major network modifications or the integration of new renewable generation to verify compliance with IEEE Std. 519-2022 and EN 50160 and to confirm that no unexpected resonance conditions have developed.

5. Conclusions

This study presents an analysis of the conditions leading to harmonic resonance in medium-voltage power distribution networks, with particular emphasis on the influence of photovoltaic systems, cable lines, and weak-grid conditions. A frequency-dependent equivalent analytical model of the distribution network, based on lumped inductive and capacitive parameters, has been developed to enable practical engineering assessment of resonance conditions and the frequency-dependent characteristics of the network. The performed frequency-domain analysis demonstrates that the increasing penetration of cable lines and inverter-based generation sources leads to an increase in the equivalent shunt capacitance and consequently to a reduction in the resonance frequency. It has been established that, in the presence of long distribution feeders and low short-circuit power, the resonance region may shift toward lower frequencies, approaching the characteristic har-

monic components generated by power electronic converters. The obtained results indicate that the most unfavorable operating conditions occur under the combined presence of high photovoltaic generation, low daytime loading conditions, reverse power flow, a significant share of cable lines, and limited short-circuit power. Furthermore, the combined influence of photovoltaic penetration and weak-grid conditions results in a substantially greater shift of the resonance frequency than the influence of each factor considered separately, highlighting the importance of evaluating these parameters simultaneously during engineering studies of modern distribution networks. The analysis confirms that current development trends in power distribution networks—including the increasing share of cable sections, the widespread deployment of photovoltaic systems, and the growing penetration of power electronic converters—create conditions for an increased risk of harmonic resonance. These findings emphasize the necessity of performing preliminary frequency-dependent assessment of network characteristics and resonance conditions during the integration of new photovoltaic generation capacities and the reconstruction of existing distribution feeders. The present analysis further indicates that impedance-based resonance assessment should become a routine part of distribution-network planning, particularly for feeders with high photovoltaic penetration, long underground cable sections, and limited short-circuit power. The proposed analytical model can be used as a practical engineering tool for the preliminary assessment of harmonic resonance risk in medium-voltage distribution networks. Its main advantages include its relatively simple structure, computational efficiency, and the possibility of performing resonance assessment using a limited set of readily available operational network parameters. Although the numerical results presented in this study correspond to a representative 20 kV distribution feeder, the proposed analytical methodology is not limited to this voltage level. The same modeling approach can be applied to other medium-voltage distribution networks and, after appropriate adaptation of the equivalent network parameters, may also be extended to distribution systems operating at other voltage levels.

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