

Article

Signatures and Mechanism Analysis of Converter-Grid Subsynchronous Oscillations

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Abstract: In the last decade, a rather new phenomenon related to subsynchronous oscillations (SSO) in a wide frequency range has emerged in modern power grids with power converters. The consequences of these oscillations can be severe system accidents, which have already occurred in various power systems. Taking into account the importance of studying such oscillations for effective mitigation and the existing gaps in understanding the mechanisms of SSO occurrence due to different combinations of used controllers in the inverter control system, as well as the grid parameters, a frequency analysis of simplified grid inverter models is performed. As a result, five different mechanisms of SSO occurrence, the affecting factors and the level of inverter model detail required for the adequate study of SSO are justified. The developed detailed state-space model allowed for verifying the obtained results, as well as identifying an additional sixth mechanism of SSO occurrence. The common condition for the occurrence of all the identified SSO mechanisms is a weak grid with a short-circuit ratio of less than two. The results of control hardware-in-the-loop testing confirmed the conclusions drawn. As a result, a classification of SSO occurrence mechanisms was formed, reflecting their causes and distinctive features.



Citation: Askarov, A.; Bay, Y.; Ufa, R.; Radko, P.; Ilyushin, P.; Suvorov, A. Signatures and Mechanism Analysis of Converter-Grid Subsynchronous Oscillations. *Mathematics* **2024**, *12*, 3884. <https://doi.org/10.3390/math12243884>

Academic Editors: Helga Silaghi and Claudiu Raul Costea

Received: 20 November 2024

Revised: 7 December 2024

Accepted: 8 December 2024

Published: 10 December 2024



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Keywords: inverter-based resources; subsynchronous oscillation; stability; weak grid; classification of SSO

MSC: 93D05

1. Introduction

Modern power systems are undergoing significant changes in the structure of generating capacities and process dynamics, which are associated with the significant development and widespread introduction of inverter-based resources [1–3]. IGBT transistors are mainly used, but new materials are being developed that will further improve their properties and capabilities [4,5]. On the one hand, the widespread introduction of renewable energy sources has increased the response speed and flexibility in the power system control. On the other hand, their unique properties, such as fast performance, small time constants in control loops, and a wide variety of generating unit capacities, have led to a radical change in the dynamic properties of power systems and the emergence of new problems related to power system stability [6,7].

These features of power converters and their control systems lead to a variety of interactions between different control loops within a single device and between such devices as a whole. Moreover, this interaction can lead to oscillations covering a wide frequency spectrum, which are referred to as wide-band oscillations in the literature [8]. Over the last decades, more than 20 different cases involving wide-band oscillations have occurred in the world [9]. Among them, it is necessary to highlight the cases with subsynchronous oscillations (SSO), which were associated with the operation of the control system of grid

inverters, or the converter-grid oscillations [10,11]. The latter is relevant because, in such cases, the mechanism of SSO occurrence becomes extremely complex, especially due to the emerging dependence of oscillations on the current operating state of the power grid, in particular, on the grid strength [12,13]. Moreover, the latter is pointed out as one of the main impact factors limiting the large-scale penetration of inverter-based resources [14,15].

The fundamental processes that lead to SSOs as a result of the grid inverter operation have been studied by various research teams. A significant contribution to the development in this field was made by the IEEE IBR SSO Taskforce chaired by Prof. L. Fan. The review papers on wide-band oscillations that occurred in various power systems presented by these experts show the extreme complexity and diversity of causes and conditions of their occurrence [8,16]. General issues related to the connection of grid inverters to a weak grid are considered in [17,18]. Studies related to the possibility of connecting Type-4 wind turbine generators into a weak grid are given in [19]. With a simplified model of a grid-side converter, in which only an inner current control loop (ICCL) is used, it is shown that oscillations with frequency from 100 to 200 Hz can occur in the power grid. Moreover, their damping is possible by the appropriate tuning of the control system. It should be noted that the obtained results do not show any low-frequency oscillations, since their simulation without taking into account the mathematical model of outer control loops and phase-locked loop (PLL) controller is complicated. The study of such oscillations by considering these control loops in the models is discussed in [20–22]. In [21], it is concluded that it is necessary to ensure the possibility of a Type-4 wind turbine generator to participate in the grid voltage regulation. Obviously, this can be achieved by increasing the response of the voltage controller [23,24]. However, this can lead to the occurrence of resonance in the electrical network. In particular, this is evidenced by real-world events [25]. Moreover, the experts achieved the elimination of oscillations only by reducing the gain in the voltage controller. In addition, it is shown in [26] that similar SSOs can occur when replacing the voltage controller with a reactive power controller.

Considering the significant impact of outer control loops on the SSO, two basic control loops in d -axis within the dq -control in synchronous reference frame of the grid inverters are mainly considered in detail in the literature: (i) the active power controller and (ii) the DC-link voltage controller. In the first case, the research results show the existence of only one oscillatory mode with a frequency of less than 10 Hz due to the response to the weak grid conditions [17,27,28]. In the second case, SSOs also occur, which, among other things, lead to torsional oscillations at nearby synchronous generators [29]. However, different from the active power controller, there are two oscillatory modes, which is proved by the eigenvalue analysis in [30]. In further studies, it is proved that both modes are related to the DC-link voltage controller, and the dominant mode depends on the PLL bandwidth [31]. Also in [32], the low-frequency SSO in a Type-3 wind turbine generator operating in a weak grid was investigated. Moreover, the studies were performed on a simplified model excluding the grid dynamics. Similar studies demonstrated the SSOs with frequencies of 10 Hz [18] and 9 Hz under voltage sags [33]. For the Type-4 wind turbine generators, similar oscillations with a frequency of 6 Hz occurred [23]. From the analysis of the results of the above papers, it follows that the interaction between the voltage controller and the PLL controller leads to oscillations, but the mechanism of this mutual impact remains undisclosed. Moreover, the PLL itself may be the cause of SSO. The papers [34,35] are devoted to the study of this issue. The authors in [36] have proved via the analysis of participation coefficients that the PLL controller is the cause of SSOs. The latter can be referred to as the use of a common approach to PLL tuning, which does not consider the issues of stable operation of the grid inverter in various operating states, especially in weak grid conditions [37]. This issue has already been shown in practice. In three different power systems under weak grid conditions, SSOs with different frequencies occurred [17,27,30]. Under other conditions, the main difference was in the PLL bandwidth. Therefore, it can be assumed that the character of SSO directly depends on the PLL tuning. In this regard, by controlling the character of SSOs, it is possible to form a direction to eliminate them. The

study of the PLL impact on the stable operation of the inverter can also be found in [35]. On the basis of the performed analysis, Table 1 presents a brief description of the current research on the topic.

Table 1. A brief analysis of previous research.

Ref.	SSO Characteristics	Cause of SSO
[17]	≈ 3 Hz	interaction of PLL and weak grid
[18]	≈ 10 Hz	interaction of PLL and DC-link voltage controller within Type-4 wind turbine generator operation
[19]	over 50 Hz	interaction of inner current control loop and weak grid
[20]	low-frequency	interaction of AC voltage controller and weak grid within Type-4 wind turbine generator operation
[21]	low-frequency	interaction of AC voltage controller and weak grid within Type-4 wind turbine generator operation
[22]	≈ 1.5 Hz	interaction of PLL and AC voltage controller
[23]	≈ 6 Hz	interaction of DC-link voltage controller and weak grid within Type-4 wind turbine generator operation
[24]	≈ 3 Hz	interaction of AC voltage controller and active power controller
[26]	≈ 3 Hz	interaction of active power controller and AC voltage/reactive power controller
[27]	aperiodic instability	impact of PLL on HVDC
[28]	from 3 Hz to 40 Hz	interaction of power controllers, voltage controller and PLL with weak grid within Type-4 wind turbine generator operation
[29]	around 40–50 Hz	interaction of outer and inner control loops within Type-4 wind turbine generator operation
[30]	from 15 Hz to 40 Hz	interaction of Type-4 wind turbine generator controllers with weak grid
[31]	from 10 Hz to 40 Hz	interaction of PLL and weak grid within Type-4 wind turbine generator operation
[32]	below 2 Hz	interaction of DC-link voltage controller and weak grid within Type-3 wind turbine generator operation
[33]	≈ 9 Hz	operation of AC voltage controller within Type-3 wind turbine generator operation
[34]	over 50 Hz	operation of PLL within Type-4 wind turbine generator operation
[35]	≈ 5 Hz	operation of PLL
[36]	from 16 Hz to 50 Hz	interaction of PLL and weak grid

Thus, the presented brief literature review shows that there are various mechanisms of SSO occurrence due to the interaction between the inverter control system and the grid operating conditions. Moreover, some results contradict each other, which indicates the diversity of occurring SSOs and the need to classify the mechanisms of their occurrence. In this paper, a comparative analysis of the mechanisms of oscillation occurrence when different controllers are used in the grid inverter control system is carried out, which has not been performed before. This approach will allow an understanding of whether SSOs have one mechanism of occurrence or whether the mechanisms are different. At the same time, this paper defines for each identified mechanism the necessary level of inverter model detail for its reproduction, which is also not fully disclosed in earlier studies. Moreover, all obtained conclusions will be verified comprehensively, not only by means of frequency and time-domain analysis but also by hardware testing. The contributions of the paper are as follows:

1. The analysis of various stages of simplification of the grid inverter mathematical model is carried out, which allowed identifying five different mechanisms of SSO occurrence and determining the extremal grid conditions affecting them.
2. The detailed state-space model of the grid inverter in a synchronous reference frame is developed, which is used to identify the mechanism of SSO occurrence undetected by simplified models.
3. The classification of the mechanisms of SSO occurrence is proposed, taking into account the applied controllers and their tuning, PLL bandwidth, as well as the external grid parameters, which affect the character of SSO.

The paper is organized as follows. Section 2 discusses the test electrical network and the considered inverter control algorithms. Section 3 presents the results of the analysis of simplified mathematical models of the test scheme with their increasing complexity. Frequency analysis is performed for each model, revealing the mechanism of SSO occurrence and the affecting factors. In Section 4, a detailed state-space model of the considered system with different control approaches for the grid inverter is developed. In addition, this section presents the results of time-domain simulation in PSCAD software v5.0.2.

Section 5 presents the results of control hardware-in-the-loop testing using a STM32-based microcontroller. Section 6 summarizes the results obtained and presents the classification of SSO mechanisms due to the interaction between the inverter control system and the external grid. The Conclusion draws the main conclusions of the paper.

2. System Structure

Figure 1 shows the diagram of the considered electrical network with a grid-following inverter. The structure of the considered outer control loops is shown in Figure 2. In the DC-link of the inverter, an ideal DC voltage source U_{dc} is connected. Such an approach is widely used in the analysis of control algorithms for the grid inverters and allows obtaining generalized results without referring to a specific generation unit.

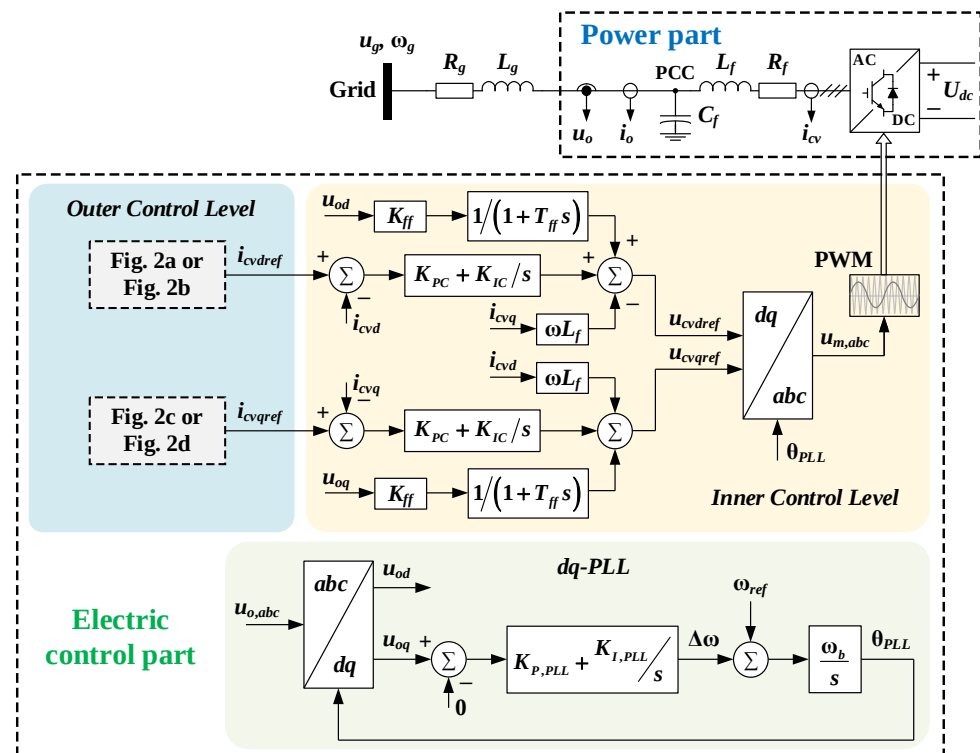


Figure 1. Diagram of the considered electrical network with a grid-following inverter.

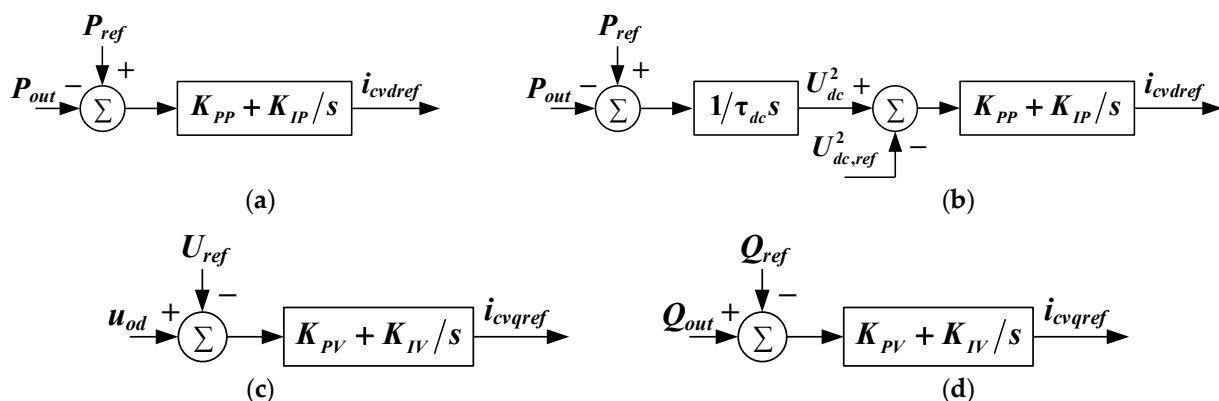


Figure 2. Structures of the outer control loops: (a) P-V Control, (b) P-Q Control, (c) DVC-V Control, (d) DVC-Q Control.

As can be seen from Figure 1, for a three-phase inverter, a decoupled active and reactive power control is implemented in a synchronous $d-q$ reference frame. For this purpose, the amplitude-invariant Park transformation is used with the d -axis aligned with

a voltage vector, so AC current is decoupled into active and reactive power components, i_d and i_q , respectively.

Two control levels can be defined within the inverter control system: (i) outer control level and (ii) inner control level. At the same time, within the outer control level, which accordingly forms the reference currents $i_{cvdqref}$, different approaches to controlling the active and reactive power of the inverter can be implemented [38–40]. As a result, the mechanism and causes of oscillations in the power grid may differ depending on the grid inverter control strategy used. Therefore, the four most common control approaches are discussed in this paper:

1. P-V Control—active power and AC voltage control (Figure 2a,c),
2. P-Q Control—active and reactive power control (Figure 2a,d),
3. DVC-V Control—DC-link and AC voltage control (Figure 2b,c),
4. DVC-Q Control—DC-link voltage and reactive power control (Figure 2b,d).

The inner control level of the inverter consists of the ICCL with cross-coupling terms and voltage feedforward [41], which forms the reference voltages $u_{cvdqref}$, and the pulse-width modulation (PWM) block, which forms control pulses for the power semiconductor switches of the inverter. The current saturation algorithm based on the vector amplitude limitation ($I_{\max} = 1.2$ pu) is also taken into account [42]. Within the conventional grid-following control, it is assumed that the synchronization of the inverter with the AC grid is performed using a PLL controller. This controller uses the three-phase voltage signal to form the required phase angle and can have different structures [43,44]. In this paper, the classical structure of dq -PLL is adopted, which is shown in Figure 1.

The presented structural diagrams of the control algorithm (Figures 1 and 2) allow forming the necessary differential equations to describe the analytical model of the inverter control system. However, for a complete representation, a system of differential equations describing the network dynamics in dq -frame should also be given as shown in Equation (1). Taken together, a complete analytical model of the considered system with different approaches to the grid inverter control can be implemented.

$$\begin{cases} \frac{di_{cvd}}{dt} = \frac{\omega_b}{L_f} \left(u_{cvdref} - u_{od} - i_{cvd}R_f + i_{cvq}L_f\omega_g \right) \\ \frac{di_{cvq}}{dt} = \frac{\omega_b}{L_f} \left(u_{cvqref} - u_{oq} - i_{cvq}R_f - i_{cvd}L_f\omega_g \right) \\ \frac{du_{od}}{dt} = \frac{\omega_b}{C_f} \left(i_{cvd} - i_{od} + u_{oq}C_f\omega_g \right) \\ \frac{du_{oq}}{dt} = \frac{\omega_b}{C_f} \left(i_{cvq} - i_{oq} - u_{od}C_f\omega_g \right) \\ \frac{di_{od}}{dt} = \frac{\omega_b}{L_g} \left(u_{od} - i_{od}R_g - u_g \cos \delta\theta_{PLL} + i_{oq}L_g\omega_g \right) \\ \frac{di_{oq}}{dt} = \frac{\omega_b}{L_g} \left(u_{oq} - i_{oq}R_g + u_g \sin \delta\theta_{PLL} - i_{od}L_g\omega_g \right) \end{cases} \quad (1)$$

where ω_b is the base grid frequency, R_f , L_f and C_f are the LC-filter parameters, L_g and R_g are the equivalent inductance and resistance from the point of common coupling (PCC) to the grid, respectively, i_{cv} is the output current of the inverter, u_g and ω_g are the grid voltage and frequency, respectively, u_o and i_o are the voltage and current at the PCC behind the LC-filter, respectively, and θ_{PLL} is the PLL phase angle.

3. Analysis of the Mechanism of SSO Occurrence

To determine the mechanism and causes of oscillations, it is necessary to form simplified dependencies that would clearly reflect the interaction of different controllers with each other and the operating conditions of the power grid. For this purpose, the grid inverter with the conventional grid-following control algorithm can be simplified as a current source [45,46]. Taking into account the presented control system, the output values are the currents i_{od} and i_{oq} (Figure 3). In addition, since this paper considers a relatively slow spectrum of processes, the ICCL is approximated as a first-order lag function with a time constant τ_{cc} , which is determined by the equation $\tau_{cc} = X_g/(\omega_b \cdot K_{PC})$, where X_g is the

grid inductive reactance in per units, including the equivalent grid inductance L_g and the filter in inductance L_f , K_{PC} is the ICCL proportional gain [47].

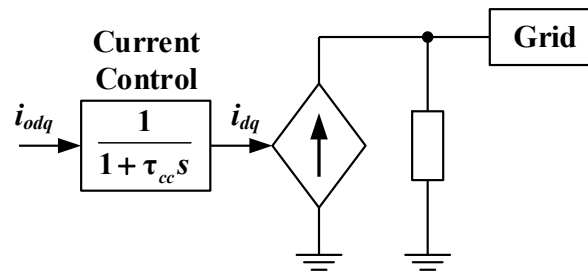


Figure 3. Simplified representation of a grid-following inverter.

3.1. Simplified Model of Grid Inverter with Active Power Controller

For the first considered simplified model of the grid inverter, the dynamics of the PLL controller and the external grid are excluded. The latter is generally represented only by the inductive resistance X_g . Considering the assumptions for Equation (1), Equation (2) is obtained:

$$\begin{cases} u_{od} = U_o = U_g \cos \delta - X_g i_{oq} \\ u_{oq} = 0 = -U_g \sin \delta + X_g i_{od} \end{cases} \quad (2)$$

where U_g is the rms grid voltage, and δ is the phase angle of U_o at the PCC.

Based on the trigonometric identity, the grid voltage can be represented as Equation (3) by considering the second equation of (2):

$$U_g \cos \delta = \sqrt{U_g^2 - (U_g \sin \delta)^2} = \sqrt{U_g^2 - (X_g i_{od})^2} \quad (3)$$

Then, the obtained Equation (3) is substituted into the first equation of (2) and its linearization can be performed (4):

$$\Delta u_{od} = - \frac{X_g}{\underbrace{\sqrt{\left(\frac{U_g}{X_g i_{od}}\right)^2 - 1}}_a} \Delta i_{od} - X_g \Delta i_{oq} = -a \Delta i_{od} - X_g \Delta i_{oq} \quad (4)$$

From the obtained Equation (4), it can be seen that with the increase of the inverter load only by the active power, which corresponds to the current i_{od} , the voltage at the PCC will decrease, which corresponds to the fundamental electrical laws. On the basis of the instantaneous power theory, the formula for the active power, taking into account the zero component for the q -axis voltage, can be written and linearized (5) by substituting Equation (4):

$$P = u_{od} \cdot i_{od} \Rightarrow \Delta P = u_{od} \cdot \Delta i_{od} + i_{od} \cdot \Delta u_{od} = \underbrace{u_{od} \Delta i_{od}}_{\Delta P_1} - i_{od} \left(\underbrace{a \Delta i_{od}}_{\Delta P_2} + \underbrace{X_g \Delta i_{oq}}_{\Delta P_3} \right) \quad (5)$$

It follows from the obtained Equation (5) that the increment of active power depends on the change of two components: (i) d -axis current and (ii) voltage at the PCC, which are expressed through the increment of dq -axes currents, depending on the grid inductive resistance X_g and the inverter active power load i_{od} . The increments of currents are formed by the controllers in the dq -axes (Figure 2a,c), as well as by the ICCL. The common expression for the controllers taking into account the ICCL operation in the dq -axes is shown in Equation (6), where the superscript 'ol' means the open-loop transfer function. By substituting the specific coefficients, the transfer function of the controllers for the d - or q -axis is obtained. The gain $G_{PC}^{ol}(s)$ that forms the current Δi_{od} is given in Equation (6), which is written for both the active power controller and the ICCL, and for the corresponding

closed-loop transfer function $G_{PC}^{cl}(s)$ in Equation (7), the negative feedback is the value $u_{od} = U_o$, where the superscript 'cl' means the closed-loop transfer function. This function corresponds to the first active power component ΔP_1 in Equation (5).

$$G^{ol}(s) = \left(K_P + \frac{K_I}{s} \right) \left(\frac{1}{1 + \tau_{cc}s} \right) \quad (6)$$

$$G_{PC}^{cl}(s) = \frac{G_{PC}^{ol}(s)}{1 + U_o \cdot G_{PC}^{ol}(s)} = \frac{K_{PP}s + K_{IP}}{\tau_{cc}s^2 + (K_{PP}U_o + 1)s + K_{IP}U_o} \quad (7)$$

The current Δi_{oq} is formed by the voltage controller (Figure 2c), which is part of the outer control loop, and the ICCL, according to Equation (6). The positive feedback, which is used in the voltage controller, is formed based on Equation (8). Given this, the closed-loop transfer function $G_{VC}^{cl}(s)$ can be written as (9), in which the feedforward gain is equal to one and the feedback gain is the product of $G_{VC}^{ol}(s)$ and X_g .

$$\Delta U_o = -X_g \Delta i_{oq} \quad (8)$$

$$G_{VC}^{cl}(s) = \frac{1}{1 + X_g \cdot G_{VC}^{ol}(s)} = \frac{\tau_{cc}s^2 + s}{\tau_{cc}s^2 + (K_{PV}X_g + 1)s + K_{IV}X_g} \quad (9)$$

The obtained Equations (5)–(9) form the transfer function representing the impact of active power and voltage controllers on the inverter output active power taking into account the grid inductive resistance. The structural diagram of the transfer function is shown in Figure 4. It should be noted that for the assumed conditions, when using the reactive power controller (Figure 2d) instead of the voltage controller, the voltage deviation Δu_{od} has no impact on the reactive power deviation, i.e., $\Delta Q = -i_{oq} \cdot \Delta u_{od} - u_{od} \cdot \Delta i_{oq} \approx u_{od} \cdot \Delta i_{oq}$, since $i_{oq} = 0$. On this basis, when a reactive power controller is used, the transfer function $G_{VC}^{cl}(s)$ (9) takes the value of one.

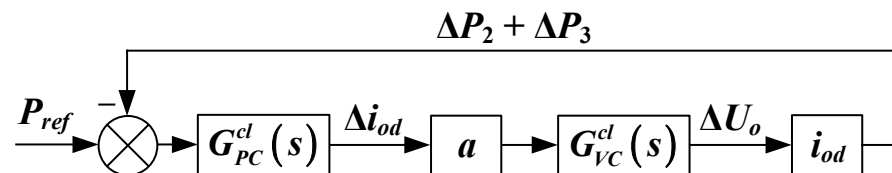


Figure 4. Structural diagram of the closed-loop transfer function representing the interaction of active power and voltage controllers.

Therefore, it is possible to consider the impact of each component on the inverter output active power separately. For this purpose, the gains for the open-loop transfer functions are written in the form of Equations (10) and (11), reflecting the impact of changing the active power reference on the deviations of the d -axis current Δi_{od} (ΔP_1) and the voltage Δu_{od} ($\Delta P_2 + \Delta P_3$).

$$G_1^{ol}(s) = G_{PC}^{ol}(s) \cdot \left(U_o - a \cdot G_{VC}^{cl}(s) \cdot i_{od} \right) \quad (10)$$

$$G_2^{ol}(s) = G_{PC}^{ol}(s) \cdot \left(-a \cdot G_{VC}^{cl}(s) \cdot i_{od} \right) \quad (11)$$

For the obtained Equations (10) and (11), the root locus analysis is used, which allows determining the stability of the closed-loop transfer function by the value of the gain at the point at which the root locus branches intersect the imaginary axis. If this gain is less than 1, the closed-loop system is unstable for the considered steady-state operating point. The root loci corresponding to Equations (10) and (11) are shown in Figure 5.

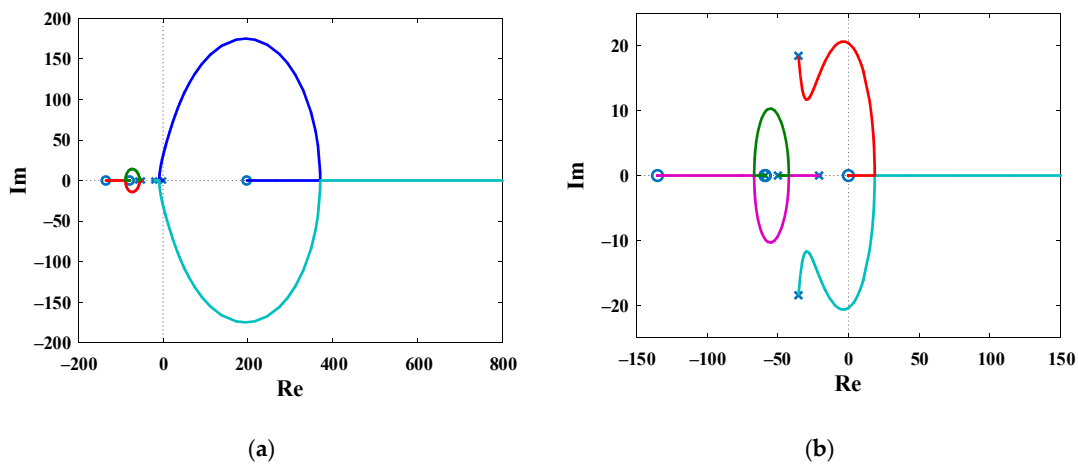


Figure 5. Root loci with $X_g = 0.8$, $\tau_{cc} = 0.017$, $i_{od} = 1$, $U_o = 1$, $K_{PP} = 0.2$, $K_{IP} = 27$, $K_{PV} = 0.25$, and $K_{IV} = 22$ for the open-loop transfer functions: (a) $G_1^{ol}(s)$, (b) $G_2^{ol}(s)$.

Figure 5 shows the pole movement trajectory to zeros in different colors—the four colors correspond to the trajectories of four poles and are only for illustrative purposes. The obtained root locus branches for both control loops show that the pole movement trajectory to zeros passes through the right half-plane. Consequently, under certain conditions, oscillations in the inverter output active power may occur, the cause of which may be either the loop forming the current Δi_{od} or the loop forming the voltage Δu_{od} . From the obtained root locus for the first considered control loop $G_1^{ol}(s)$, it follows that the poles are towards zero in the right half-plane (Figure 5a), which refers to the multiplier $(U_o - a \cdot G_{VC}^{cl}(s) \cdot i_{od})$. The numerator of this function is a second-order equation. Hence, based on Vieta's formulas, it can be concluded that the roots will have different signs when the constant term is less than zero. The constant term c of this equation has the following form (12):

$$c = \frac{K_{IV} \cdot U_o \cdot X_g}{\tau_{cc} \cdot (U_o - a \cdot i_{od})} \quad (12)$$

Based on the Formula (12), the roots of the equation, which are the considered zeros, will be located in different planes under the condition $a \cdot i_{od} > U_o$. In this case, it is the control loop forming the current Δi_{od} that will cause the active power oscillations. It should be noted that the cause of oscillations is not the tuning of the control loop itself, but the interaction of the voltage and active power controllers, since the zero in the right half-plane occurs due to the multiplier, which includes the voltage controller $G_{VC}^{cl}(s)$. From the obtained equations it follows that the conditions leading to the oscillations are the increase in the grid inductive resistance X_g , which is proportional to the variable a , the increase in the active power load of the inverter, which corresponds to the current i_{od} , and the decrease in the voltage U_o .

For the second control loop $G_2^{ol}(s)$, associated with Δu_{od} , the poles formed by the active power controller tend through the right half-plane to $+\infty$ and zero at the origin (Figure 5b). From Equation (11), it is obvious that this zero refers to the function of the voltage controller $G_{VC}^{cl}(s)$. The probability of oscillation also depends on the increase of X_g and i_{od} . In this case, these parameters are the gains for the open-loop function, the increase of which reduces the value of the gain at which the root locus branches intersect the imaginary axis and, consequently, reduces the stability margin.

Thus, from the two discussed mechanisms of possible oscillations, it follows that the major cause in both cases is the voltage controller (Figure 2c), which leads to the occurrence of interaction in the control of active power and voltage. Considering the impact of $G_{VC}^{cl}(s)$, it is possible to improve the stability by reducing the value of this function in steady-state, i.e., at $p \rightarrow 0$. This can be achieved by increasing the bandwidth of $G_{VC}^{cl}(s)$. To verify

this fact, an increase in the grid impedance X_g is performed, at which the undamped oscillations with increasing magnitude occur, and two different bandwidths of $G_{VC}^{cl}(s)$ are considered (Figure 6). For the initial bandwidth of $G_{VC}^{cl}(s)$, the gains for both open-loop functions are less than one, indicating instability (blue curves in Figure 6a,b). However, if the proportional gain K_{PV} is increased, which leads to an appropriate increase in bandwidth, the gain at the point of intersection of the root locus with the imaginary axis becomes greater than one and the system becomes stable (red curves in Figure 6a,b). It follows from the obtained results that an increase in the voltage controller response leads to a decrease in the interaction between the active power and voltage controllers, which contributes to an increase in the stability margin.

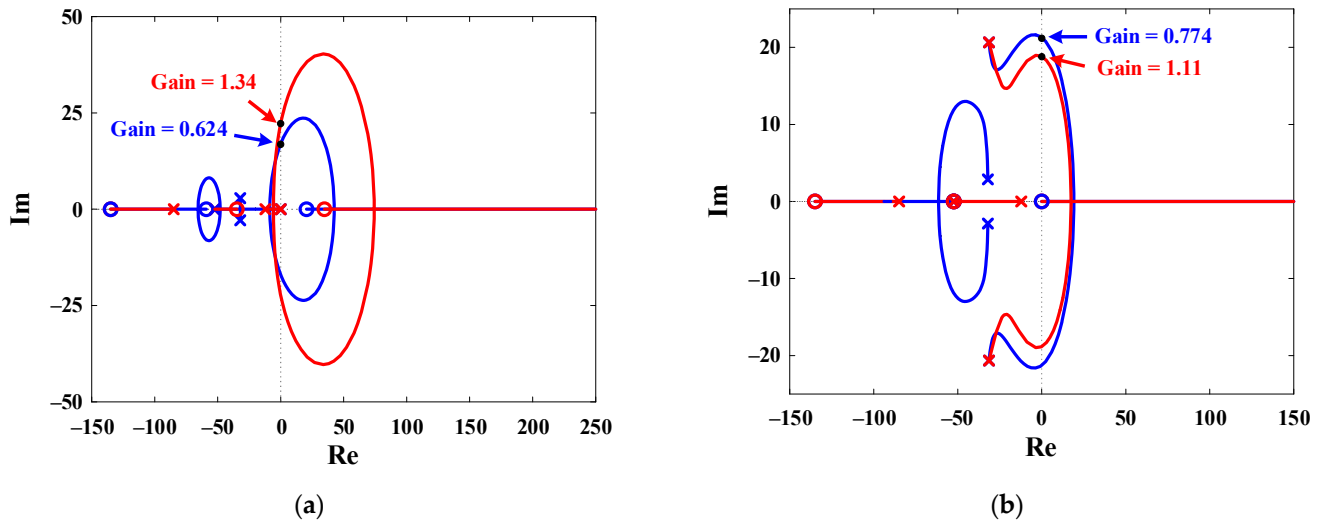


Figure 6. Root loci with $X_g = 0.9$, $\tau_{cc} = 0.0191$, $i_{od} = 1$, $U_o = 1$, $K_{PP} = 0.2$, $K_{IP} = 27$, $K_{PV} = 0.25$ (blue curves), $K_{PV} = 0.95$ (red curves), and $K_{IV} = 22$ for the open-loop transfer functions: (a) $G_1^{ol}(s)$, (b) $G_2^{ol}(s)$.

Considering the obtained cause of oscillations due to the voltage controller operation, a possible solution is to replace it with a reactive power controller (Figure 2d). For this case $G_{VC}^{cl}(s) = 1$ is set. The obtained root loci for the considered gains $G_1^{ol}(s)$ and $G_2^{ol}(s)$ are presented in Figure 7.

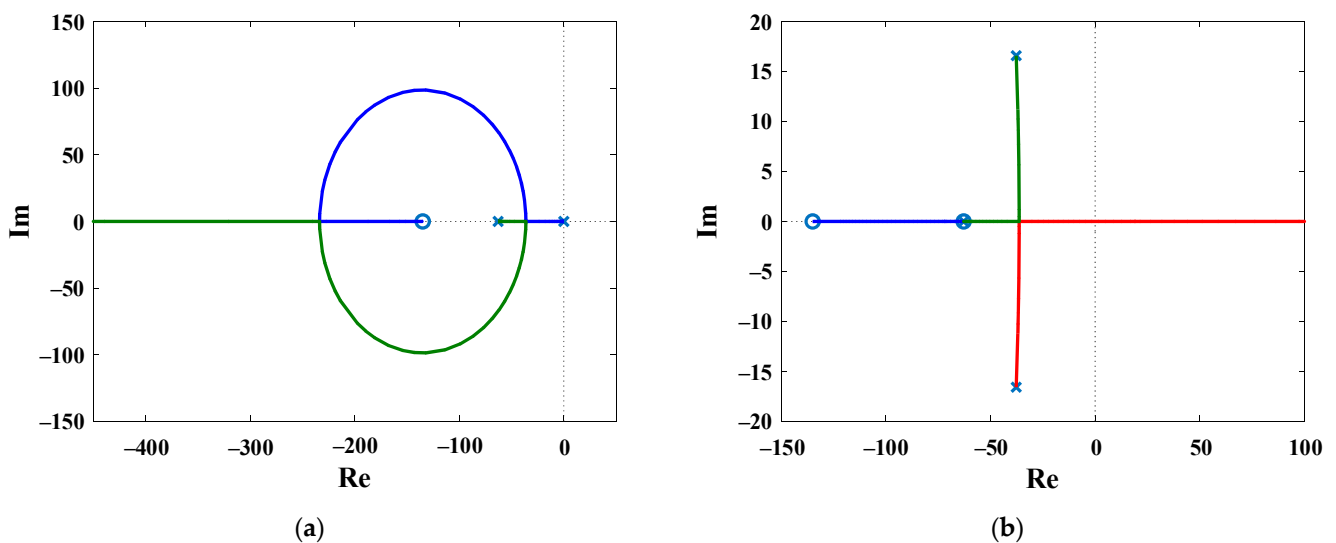


Figure 7. Root loci with a reactive power controller ($G_{VC}^{cl}(s) = 1$) and $X_g = 0.75$, $\tau_{cc} = 0.0159$, $i_{od} = 1$, $U_o = 1$, $K_{PP} = 0.2$, and $K_{IP} = 27$ for the open-loop transfer functions: (a) $G_1^{ol}(s)$, (b) $G_2^{ol}(s)$.

Figure 7a,b show that there is no intersection of the imaginary axis by the trajectories of the conjugate poles when the reactive power controller is used. Consequently, oscillations will not occur, but it follows from the root locus for the second function $G_2^{ol}(s)$ that one of the poles of the reactive power controller moves along the real axis to $+\infty$. Such a trajectory corresponds to the aperiodic instability in contrast to the oscillatory instability when the voltage controller is used. The causes of aperiodic instability are classical and are related to reaching the limit of network power transfer capability [48]. It is worth noting that despite the absence of oscillations when the reactive power controller is used, it cannot be concluded that the overall situation is improved compared to the voltage controller, since aperiodic instability occurs at a smaller value of X_g .

In addition to the controllers forming the reference q -axis current, the stability margin can be increased by means of the active power controller and the ICCL. For the first one it is necessary to reduce the bandwidth, whereas for the second one it is necessary to increase it.

3.2. Simplified Model of Grid Inverter with DC-Link Voltage Controller

In this subsection, the DC-link voltage controller (Figure 2b) is considered as a controller forming the reference d -axis current instead of the active power controller. The dynamics of the inverter DC-link can be expressed by Equation (13) [31]:

$$\tau_{dc} \frac{dU_{dc}^2}{dt} = P_{ref} - P_{out} \quad (13)$$

where $\tau_{dc} = \frac{C_{dc} U_{b,dc}^2}{2S_b}$ is the DC-link time constant, C_{dc} is the DC-link capacitance, $U_{b,dc}$ is the rated DC-link voltage, S_b is the inverter-rated capacity.

Substituting Equation (13) into the d -axis gain of the open-circuit function, Equation (10) takes the following form (14), which accounts for the dynamics of the inverter DC-link:

$$G_{1,dc}^{ol}(s) = \frac{1}{\tau_{dc}s} \cdot G_{PC}^{ol}(s) \cdot (U_o - a \cdot G_{VC}^{ol}(s) \cdot i_{od}) \quad (14)$$

The root loci for the obtained gain at different values of grid impedance are shown in Figure 8.

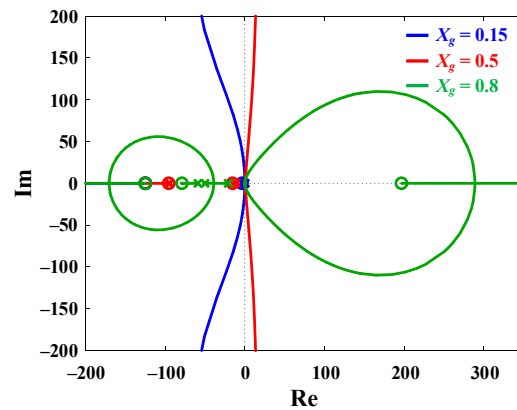


Figure 8. Root loci with $\tau_{cc} = 0.0191$, $i_{od} = 1$, $U_o = 1$, $K_{PP} = 0.2$, $K_{IP} = 27$, $K_{PV} = 0.25$, and $K_{IV} = 22$ for the open-loop transfer function $G_{1,dc}^{ol}(s)$.

It follows from Figure 8 that at $X_g = 0.15$ pu and 0.5 pu, for which the condition $a \cdot i_{od} > U_o$ is not satisfied, the branches of the root loci tend to $\pm\infty$ along the imaginary axis as the gain increases. Moreover, at $X_g = 0.5$ pu, the branches of the root locus already pass through the right half-plane at a gain less than one, which indicates the occurrence of undamped oscillations. When X_g is further increased and the above condition is satisfied, zero appears in the right half-plane, which is similar to the case described in the previous subsection when the active power controller is used. Thus, the addition of DC-link dynam-

ics has a negative impact on the stability margin and leads to the occurrence of oscillations even before the appearance of zero in the right half-plane. Moreover, such specificity is related to the appearance of conjugate roots as a result of adding DC-link dynamics to the inverter model. The replacement of the voltage controller by a reactive power controller does not improve the situation. As a result, the causes of oscillations are related to insufficient damping when adding a DC-link voltage controller, rather than to the interaction in the control of active power and voltage as in the previous case. Furthermore, the factors that reduce the stability margin are the same: an increase of both the grid impedance and the inverter load, as well as a decrease of the grid voltage.

3.3. Simplified Model of Grid Inverter with Active Power Controller and PLL

To further analysis of the oscillation mechanism, the PLL controller is added to the simplified model of the grid inverter. The closed-loop transfer function of PLL is shown as (15) [49]:

$$G_{PLL}^{cl}(s) = \frac{\Delta\delta}{\Delta\delta_o} = \frac{(K_{P,PLL}s + K_{I,PLL})\omega_b}{s^2 + K_{P,PLL}\omega_b s + K_{I,PLL}\omega_b} \quad (15)$$

Furthermore, the linearization of Equation (2) is performed for the steady state under the condition $\delta = \delta_o$ (16):

$$\begin{cases} \Delta u_{od} = -U_o \sin \delta \cdot \Delta\delta - X_g \Delta i_{oq} \\ \Delta u_{oq} = -U_o \cos \delta \cdot \Delta\delta + X_g \Delta i_{od} \end{cases} \quad (16)$$

In this way, Equation (17) describing the behavior of the voltage angle δ_o at the PLL input can be derived from the second equation of (16) by substituting $U_o \cdot \cos \delta$ from the first equation of (2) and the basic representation of the voltage U_o at the PLL along the q -axis in the linearized form $u_{oq} = U_o \cdot \sin(\delta_o - \delta) \approx U_o \cdot (\delta_o - \delta) \rightarrow \Delta u_{oq} = U_o \cdot (\Delta\delta_o - \Delta\delta)$:

$$\begin{aligned} \Delta u_{oq} &= -(U_o + X_g i_{oq}) \Delta\delta + X_g \Delta i_{od} \Rightarrow \\ \Rightarrow X_g \Delta i_{od} &= X_g i_{oq} \Delta\delta + U_o \Delta\delta_o \end{aligned} \quad (17)$$

From the obtained Equation (17) the increment of the angle $\Delta\delta_o$ at the PLL input can be obtained (18):

$$\Delta\delta_o = \frac{X_g}{U_o} \Delta i_{od} - \frac{i_{oq} X_g \Delta\delta}{U_o} \quad (18)$$

As it was noted earlier, when the steady state is considered, the voltage at PCC can be represented by the d -axis voltage, i.e., $U_o = u_{od}$. Taking into account this condition, the second equation of (2) is substituted into the first equation of (16) and Equation (19) is obtained, representing the voltage change at the PCC considering the PLL controller operation. It can be seen that the difference from Equation (10) consists in the appearance of an additional component depending on the increment of the angle $\Delta\delta$ at the PLL output.

$$\Delta U_o = -X_g i_{oq} \Delta\delta - X_g \Delta i_{oq} \quad (19)$$

Adding the obtained Equations (18) and (19) to the closed-loop transfer function (Figure 4), the PLL impact on the mechanism of oscillation occurrence will be taken into account. The extended structural diagram is shown in Figure 9.

Similarly to the previous analysis of the emerging oscillations, the root loci for the gain $G_{PLL}^{cl}(s)$ is plotted, which is highlighted in Figure 9. The PLL tuning for the grid inverter is performed in each specific case and depends on the type of primary source, equipment vendor, which may or may not provide an option to change the PLL parameters, the range of which is already limited by the stability of the PLL algorithm. In addition, a vivid example of the fact that PLL in different cases is used with different bandwidths are examples of real-world oscillation events. For example, three cases of oscillations that were related to the operation of the grid inverter in a weak grid are presented in the following papers [17,27,30]. In all cases, the cause of oscillations was the same—weak grid

conditions, but the oscillations had different nature and frequency: in the first case, the latter was 4 Hz, in the second case—less than 4 Hz, and in the third case—in the range of 20 to 40 Hz. The reason for the difference in these real oscillations is the different PLL tuning in practical power plants. In this regard, the bandwidth of the PLL is one of the key factors that determines the nature of the oscillations. That is why several variants of PLL bandwidth are discussed in this paper. Root loci for three different cases with respect to the PLL bandwidth are shown in Figure 10. For the third case it is assumed $G_{PLL}^{cl}(s) = 1$, which corresponds to an infinite PLL bandwidth. It follows from Figure 10 that with the increase in the PLL bandwidth, there is an increase in the gain values obtained at the intersection of the root loci branches with the imaginary axis, which indicates an improvement in the stability margin.

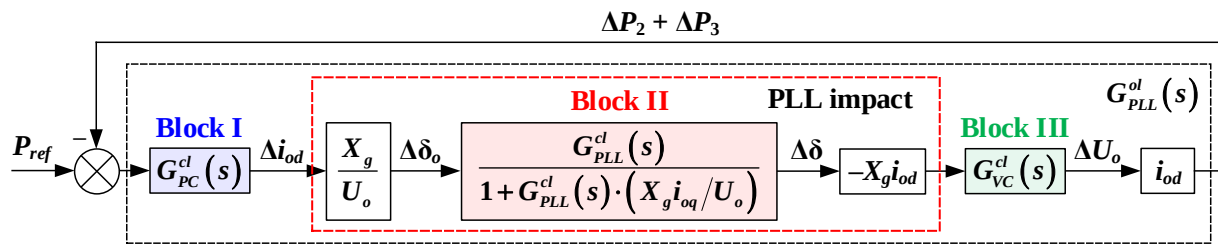


Figure 9. Structural diagram of the extended closed-loop transfer function reflecting the PLL impact on the occurrence of oscillations.

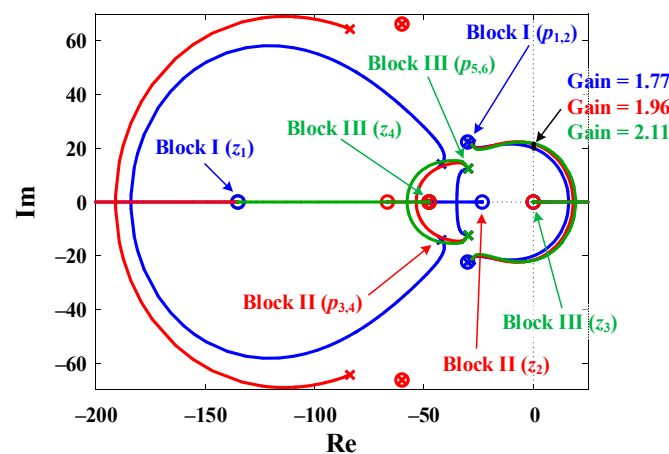


Figure 10. Root loci for the open-loop function $G_{PLL}^{ol}(s)$ at different PLL bandwidths: 13 Hz (blue curves), 30 Hz (red curves), ∞ (green curves).

In order to identify the mechanism of oscillation occurrence, the transfer functions that correspond to each control loop are determined from the general structure of $G_{PLL}^{ol}(s)$. Thus, Block I in Figure 9 corresponds to the active power controller $G_{PC}^{cl}(s)$, Block II reflects the impact of the PLL controller, and Block III is related to the voltage controller $G_{VC}^{cl}(s)$. In Figure 11, the blue color indicates the poles and zeros corresponding to each of the above blocks at the PLL bandwidth of 13 Hz. For Block I the pair of conjugate poles $p_{1,2} = -28.6 \pm 21.7j$ and zero $z_1 = -135$ are obtained. Block II has a pair of conjugate roots $p_{3,4} = -41.9 \pm 14.2j$ and zero $z_2 = -23.3$, which is equal to the ratio of the integral and proportional gains of the PLL. Block III has conjugate poles $p_{5,6} = -29.7 \pm 12.5j$ and two zeros: at the origin (z_3) and at the point $z_4 = -47.6$, the value of which is in inverse proportion to the time constant of the ICCL. Moreover, the poles of Block III move to z_2 and z_4 , the poles of Block II—to z_1 and $-\infty$, and of Block I to the origin of coordinates (z_3) and $+\infty$, respectively. On this basis, the poles of Block I pass through the right half-plane, which is the major cause of the oscillations. Thus, the mechanism of oscillation occurrence is the same as for the case considered earlier without the PLL operation. Moreover, if the voltage

controller is replaced by a reactive power controller, the conjugate poles of Block I intersect the imaginary axis only at the origin, which excludes the oscillatory instability (red curves in Figure 11). The factors that increase the probability of oscillations are identical to the previous cases: the value of the grid impedance, the inverter active power load and the voltage at the PCC.

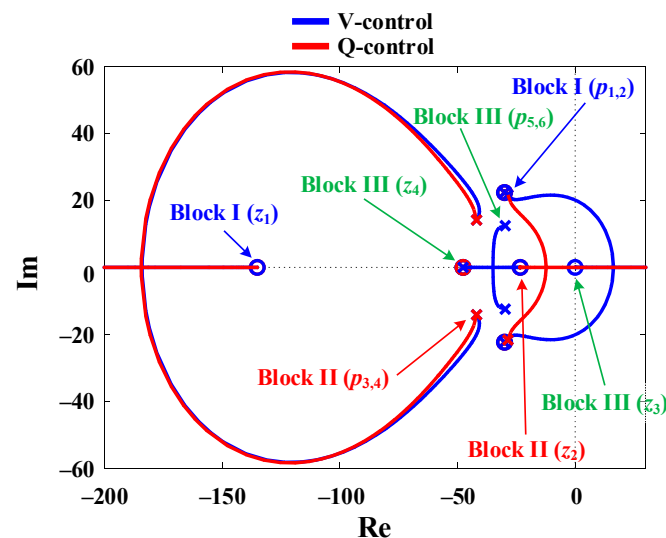


Figure 11. Root loci for the open-loop function $G_{PLL}^{ol}(s)$ at the PLL bandwidth of 13 Hz and different q -axis controllers.

3.4. Simplified Model of Grid Inverter with DC-Link Voltage Controller and PLL

Furthermore, in the extended simplified model of the grid inverter with PLL (Figure 9), the DC-link voltage controller (Figure 2a) is used instead of the active power controller (Figure 2b), which leads to the modification of Block I by adding an integrator with DC-link time constant τ_{dc} to the function $G_1^{ol}(s)$ as shown in Section 3.2. For comparison, Figure 12 shows the root loci for different d -axis controllers.

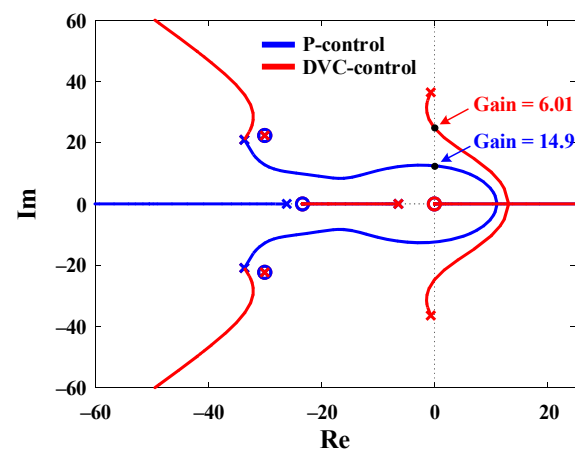


Figure 12. Root loci for the open-loop function $G_{PLL}^{ol}(s)$ at different d -axis controllers.

It follows from the obtained root loci that the addition of the DC-link voltage controller leads to a significant decrease in the gain at the intersection of the root locus branches with the imaginary axis; the value changes from 14 to 6. Consequently, adding the DC-link dynamics significantly increases the probability of oscillation occurrence. Moreover, adding the dynamics of the PLL controller does not change the situation. The use of a reactive power controller instead of a voltage controller also results in aperiodic instability.

3.5. Simplified Model of Grid Inverter with PLL and Grid Dynamics

In the previous subsections, despite the addition of all major outer and inner control loops, the inverter model is simplified due to the fact that electromagnetic transients in the electrical network are neglected. At the same time, it is known that the PLL controller with a high bandwidth under weak grid conditions can lead to undamped oscillations [50]. To analyze this mechanism of oscillation occurrence, only the PLL control loop will be further considered, while slower processes caused by other controllers will be excluded. The grid dynamics is taken into account using simple Equation (20), which is substituted into Equation (2) under the assumption that the q -axis current is zero ($i_{oq} = 0$). The obtained Equation (21) is written in a stationary reference frame related to the grid. Furthermore, Equation (21) is linearized, taking into account $U_o = \text{const}$, and the obtained equation is decomposed into the real and imaginary parts (22). It follows from Equation (22) that the change of the PLL output angle $\Delta\delta$ has a natural impact on the magnitude and angle of the voltage at the PCC. Moreover, with the increase of the inverter active power load and grid impedance, the impact of the angle $\Delta\delta$ will become stronger. Then, the imaginary part of Equation (22) is considered, which includes a differential component reflecting the grid dynamics. In fact, this equation is the feedback gain between the voltage vector at the PCC and the PLL output angle. In this regard, a minus sign should be added to initially consider a stable system. In addition, due to the consideration of fast processes, the various delays that may be caused by $abc \leftrightarrow dq$ transformations and signal filtering should be taken into account. For this purpose, a first-order low-pass filter (LPF) with time constant $T_{ff} = 0.001$ s is added to the considered system. As a result, the open-loop transfer function has the following form (23):

$$Z_g = (s + j\omega)L_g = sL_g + jX_g \quad (20)$$

$$U_o e^{j\delta_o} = U_o + (s + j\omega)L_g i_{od} e^{j\delta} \quad (21)$$

$$\begin{aligned} \Delta U_o + jU_o \Delta\delta_o &= (s + j\omega) \cdot L_g \cdot i_{od} \cdot (j\Delta\delta) \Rightarrow \\ \Rightarrow \begin{cases} \Delta U_o &= -X_g i_{od} \Delta\delta \\ U_o \Delta\delta_o &= sL_g i_{od} \Delta\delta \end{cases} \end{aligned} \quad (22)$$

$$G_{PLL+sL_g}^{ol}(s) = -s \frac{X_g}{\omega_b} i_{od} \frac{1}{1 + T_{ff}s} G_{PLL}^{cl}(s) \quad (23)$$

In the previous subsections, it was concluded that increasing the PLL bandwidth increases the stability margin. Therefore, two cases with different PLL bandwidths are considered. Figure 13 shows the Bode plots for the closed-loop transfer function of the PLL $G_{PLL}^{cl}(s)$, taking into account the LPF. In general, the result is as expected: the addition of a LPF leads to resonance with increasing PLL performance. At the same time, this characteristic did not affect the probability of oscillation occurrence in the previous subsections, since the cause of poles entering the right half-plane were other control loops. However, consideration of the grid dynamics leads to the emergence of zero at the origin of the root locus (Figure 14). Exactly to this zero the trajectory of poles movement of the PLL controller is observed, which already passes through the right half-plane that can be the cause of undamped oscillations. Moreover, from the obtained gains it follows that the major impact is in the PLL bandwidth, the increase of which leads to instability. Thus, for this mechanism of oscillations, the major cause is the delays in the PLL during the interaction with the fast dynamics of the grid. Moreover, if the ideal conditions are simulated, i.e., without delays in the form of a LPF, there are no undamped oscillations. As a result, the inevitable delays in the PLL signal, the increase in the PLL performance, the grid impedance and the inverter active power load will increase the probability of oscillations occurring due to the considered mechanism.

An important point should be noted. In this subsection, the outer control loops were not considered. However, as it was found earlier, in ultra-weak grid conditions, these controllers can also cause undamped oscillations. It is extremely difficult to take these controllers into account in simple closed-loop transfer functions when reproducing the grid

dynamics. Therefore, in the next section, a detailed analytical model of the grid inverter is developed, which allows not only to verify the results obtained using simplified transfer functions, but also to expand the understanding of the mechanism of oscillation occurrence under weak grid conditions and at different response rates of controllers.

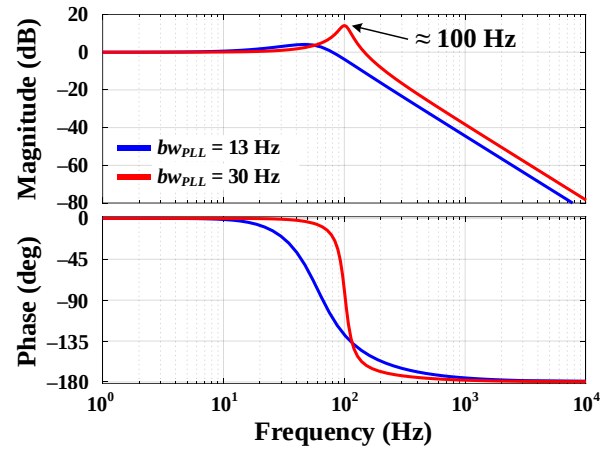


Figure 13. Bode plots of the closed-loop transfer function $\frac{1}{1+T_f s} G_{PLL}^{cl}(s)$ at different PLL bandwidths.

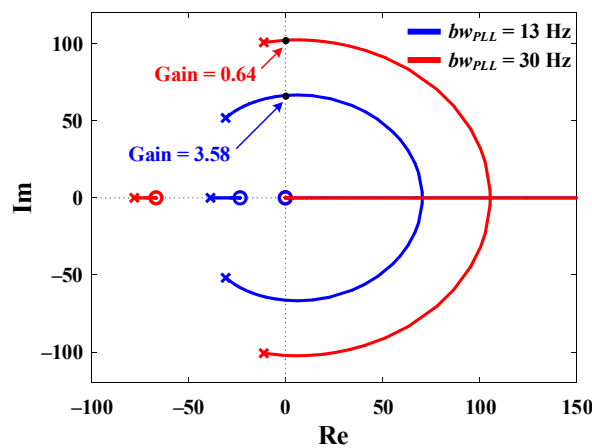


Figure 14. Root loci of $G_{PLL+sL_g}^{ol}(s)$ at different PLL bandwidths.

4. Analysis and Verification of Oscillations Mechanism Based on the Detailed Analytical Model

For the analysis of the detailed analytical model of the considered system presented in Section 2, a corresponding state–space model is developed [51]. As an example, the model for the case of P-V inverter control is shown. The state vector $\Delta \mathbf{x}$ and the input vector $\Delta \mathbf{u}$ are represented by Equation (24), considering all the parameters of the system (electric network) and control loops:

$$\begin{aligned} \Delta \mathbf{x} &= \begin{bmatrix} \Delta u_{od} & \Delta u_{oq} & \Delta i_{cvd} & \Delta i_{cvq} & \Delta \gamma_d & \Delta \gamma_q & \Delta i_{od} & \Delta i_{oq} & \dots \\ & & \Delta \varepsilon_{PLL} & \Delta \zeta_d & \Delta \zeta_q & \Delta \theta_{PLL} & \Delta u_{cd} & \Delta u_{cq} \end{bmatrix}^T \\ \Delta \mathbf{u} &= \begin{bmatrix} \Delta P_{ref} & \Delta U_{ref} & \Delta U_{grid} & \Delta \omega_{grid} \end{bmatrix}^T \end{aligned} \quad (24)$$

Using the obtained state–space model, the eigenvalues of the state matrix have been calculated, and the participation coefficients have been estimated according to the methodology used in [52]. The initial parameters of the system (Figure 1) are presented in Appendix A in Table A1. The results of the analysis are given in Tables 2 and 3. From the obtained results (Table 2) it can be seen that all eigenvalues have a negative real part. This fact indicates the stability of the system with the considered tuning parameters and control approach.

Table 2. Eigenvalue analysis for the case of P-V inverter control.

Mode	Eigenvalue	Damping Ratio	Natural Oscillation Frequency, Hz	Mainly Related State Variable
$\lambda_{1,2}$	$-406.491 \pm j3798.556$	0.106	608.01	$u_{od}, u_{oq}, i_{c vd}, i_{c vq}$
$\lambda_{3,4}$	$-445.788 \pm j3364.336$	0.131	540.13	$u_{od}, u_{oq}, i_{c vd}, i_{c vq}$
$\lambda_{5,6}$	$-297.637 \pm j395.316$	0.601	78.76	$i_{c vd}, i_{c vq}, i_{od}, i_{oq}, u_{cd}, u_{cq}$
$\lambda_{7,8}$	$-106.078 \pm j197.959$	0.472	35.74	u_{cd}, u_{cq}
$\lambda_{9,10}$	$-28.815 \pm j20.357$	0.817	5.62	$\varepsilon_{PLL}, \theta_{PLL}$
λ_{11}	-23.125	-	-	ξ_d
λ_{12}	-6.98	-	-	ξ_q
λ_{13}	-13.143	-	-	γ_d
λ_{14}	-15.451	-	-	γ_q

Table 3. Analysis of participation factors for the case of P-V inverter control.

Element	State Variables	P-V Control								
		$\lambda_{1,2}$	$\lambda_{3,4}$	$\lambda_{5,6}$	$\lambda_{7,8}$	$\lambda_{9,10}$	λ_{11}	λ_{12}	λ_{13}	λ_{14}
Grid	u_{od}	0.255	0.198	0.005	0.005	0	0	0	0	0
	u_{oq}	0.217	0.235	0.004	0.005	0	0	0	0	0
	$i_{c vd}$	0.156	0.155	0.154	0.141	0.007	0.091	0.001	0.049	0.017
	$i_{c vq}$	0.132	0.178	0.151	0.145	0.004	0.014	0.018	0	0.071
	i_{od}	0.089	0.061	0.188	0.065	0.001	0.021	0.009	0	0.004
	i_{oq}	0.077	0.076	0.184	0.096	0.005	0.001	0.005	0	0.002
Outer control loops	ξ_d	0	0	0.004	0.022	0.047	0.513	0.049	0.108	0.038
	ξ_q	0	0	0.001	0.011	0.008	0.03	0.866	0	0.084
ICCL	γ_d	0	0	0.003	0.014	0.01	0.107	0.001	0.83	0.023
	γ_q	0	0	0.003	0.014	0.014	0.078	0.036	0.003	0.715
PLL	ε_{PLL}	0	0	0.001	0.007	0.455	0.085	0.008	0.001	0.013
	θ_{PLL}	0.001	0.002	0.014	0.059	0.411	0.001	0.005	0	0.004
Voltage feedforward	u_{cd}	0.04	0.044	0.15	0.211	0.014	0.019	0.002	0.009	0.015
	u_{cq}	0.033	0.052	0.139	0.204	0.022	0.04	0	0	0.015

The use of the participation coefficients (Table 3) allows determining with which element of the system the corresponding roots are associated. The roots $\lambda_{7,8}$, $\lambda_{9,10}$ and $\lambda_{11,12}$, which have natural oscillation frequencies lower than synchronous (subsynchronous) and are directly related to the considered control loops, are of the greatest interest. Consideration of these roots allows clearly determining the cause of SSOs and instability of the grid inverter under different control methods, which were previously reflected in Section 3. Thus, the analysis of the state–space model with the plotting of root loci and definition of participation coefficients for different controllers is used for further research.

4.1. Eigenvalues Analysis of the Analytical Model of the Grid Inverter Under Different Control Methods

In this subsection, the four grid inverter control methods presented in Section 2 have been considered by varying the grid strength via the L_g value up to the instability, taking into account the full-load inverter ($P_{ref} = 1$ pu). At the same time, the impact of varying the PLL bandwidth (bw_{PLL}) on the nature of the resulting oscillations was also assessed. For the considered cases, the root loci presented in Figure 15 were obtained. The different ranges for L_g were assumed based on the obtained trends in order to better show the results of the studies.

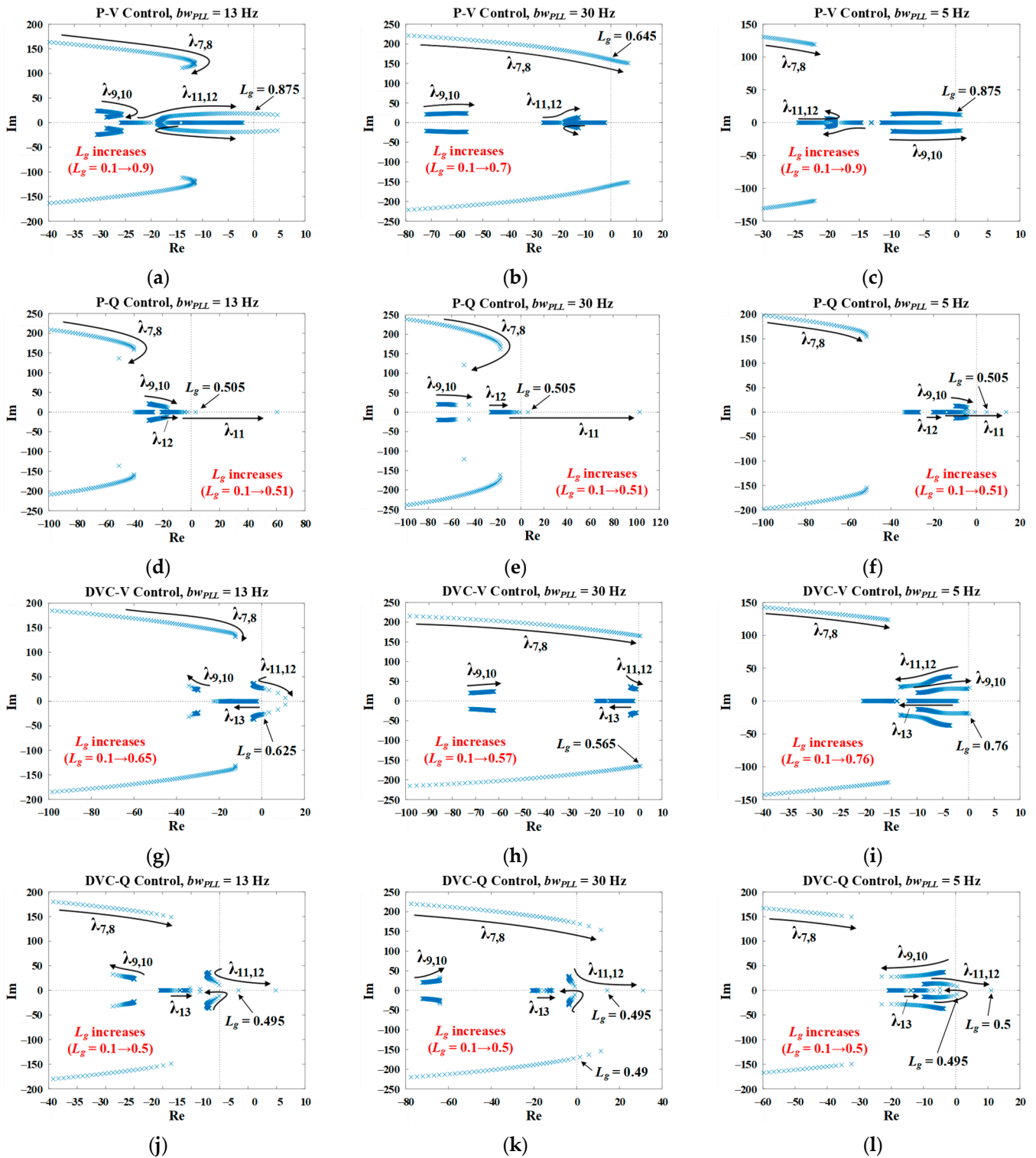


Figure 15. Root loci at L_g variation in case of different approaches to grid inverter control and PLL bandwidths: (a–c) P-V Control, (d–f) P-Q Control, (g–i) DVC-V Control, (j–l) DVC-Q Control.

Figure 15a–c show the results for the case with P-V control. As follows from Figure 15a, at the initial PLL bandwidth ($bw_{PLL} = 13$ Hz), the instability is observed at $L_g = 0.875$ pu, i.e., the short-circuit ratio (SCR) is close to one, which corresponds to the ultra-weak grid conditions. The value of SCR can be found by the formula presented in [51]. In this case, a pair of conjugate roots $\lambda_{11,12}$ is located in the right half-plane, which is associated with the operation of the outer control loops for active power and voltage. The roots belonging

to the elements of the system were determined by analyzing the participation coefficients of the system states, as it was shown earlier. In this case, an oscillatory instability with an oscillation frequency of 2.88 Hz is observed. Thus, the cause of oscillations, obtained using a detailed analytical model, coincides with the mechanism revealed by simplified models and consists in the interaction of active power and voltage control loops (Section 3.3). With increasing the PLL performance ($bw_{PLL} = 30$ Hz), the instability occurs already at a higher value of SCR ≈ 1.55 ($L_g = 0.645$ pu) and for another cause. The major factor is the LPF used for the voltage feedforward in the ICCL ($\lambda_{7,8}$). In this case, the oscillation frequency becomes equal to 25.3 Hz (Figure 15b). These results coincide with the oscillations occurring when the PLL performance is increased and the delays in the form of LPF are taken into account (Section 3.5).

In Figure 15c with the PLL bandwidth close to the response speed of the outer control loops, it is obtained that the instability occurs at the value of the grid impedance similar to the case in Figure 15a ($L_g = 0.875$ pu). However, the instability occurs due to the monotonous movement to the right half-plane of other conjugate roots— $\lambda_{9,10}$ —associated with the PLL operation. The frequency of oscillations is 1.96 Hz. In this case, the cause of oscillations is related to the insufficient damping effect of the PLL controller under weak grid conditions.

Considering the P-Q inverter control (Figure 15d–f), a fundamentally different nature of instability is observed. In the case of the initial PLL bandwidth ($bw_{PLL} = 13$ Hz), the instability is observed at $L_g = 0.505$ pu (Figure 15d), which is 42% less than the value obtained with P-V control (Figure 15a). This is evidenced by the location of the root λ_{11} of the outer active power control loop in the right half-plane. At the same time, the root λ_{11} is on the real axis, which indicates an aperiodic instability. The change of the PLL bandwidth (Figure 15e,f) does not affect both the cause of instability and the moment of its occurrence. In this case, only the location of the conjugate roots $\lambda_{7,8}$ and $\lambda_{9,10}$ changes significantly on the complex plane, as can be seen from the presented root loci. As a result, P-Q control does not allow ensuring stable operation of the power converter under ultra-weak grid conditions with SCR values close to one, without considering the installation of additional reactive power sources to regulate the voltage level at the PCC. Thus, the identified mechanism in all cases has an aperiodic nature, which coincides with the results obtained using simplified models in Section 3. The exception is the case with increased PLL bandwidth ($bw_{PLL} = 30$ Hz). In this case, the aperiodic instability is dominant, which eventually minimizes the probability of oscillations due to the PLL controller operation.

In the case of using a DC-link voltage controller (DVC-V control), an additional root (as well as the state variable) appears in the considered system, associated with the introduction of the indicated control loop. As a result, a pair of conjugate roots $\lambda_{11,12}$ of the outer active power control loop and a root λ_{13} of the outer reactive power control loop are formed in this case. The root loci for this control method are shown in Figure 15g–i. Figure 15g shows that at $bw_{PLL} = 13$ Hz, the cause of instability is the location of the roots $\lambda_{11,12}$ of the outer active power control loop in the right half-plane. Therefore, unlike P-V control, the cause of oscillations is only the active power control loop, which confirms the conclusions of Section 3.2. At the same time, the instability is observed at $L_g = 0.625$ pu, which is 28% less than the value obtained with P-V control (Figure 15a). When the PLL bandwidth is increased up to 30 Hz (Figure 15h), the roots $\lambda_{9,10}$ of the PLL are naturally moved to the left, and the instability is already observed at a smaller value of $L_g = 0.565$ pu. In the latter case, the instability is due to the roots $\lambda_{7,8}$ of the LPF used for the voltage feedforward in the ICCL, as in the similar case for P-V control (Figure 15b). When bw_{PLL} is reduced to 5 Hz for DVC-V control (Figure 15i), it follows that the stability margin under weak grid conditions increases—instability is observed at $L_g = 0.76$ pu, which is 22% higher than the value in Figure 15g. At the same time, the mechanism of oscillation occurrence also changes. The pair of conjugate roots $\lambda_{9,10}$ of the PLL is located in the right half-plane. Thus, the use of DVC-V control is somewhat different from P-V control in the nature and mechanism of oscillation occurrence. An inappropriate tuning of the active power control loop will lead

to oscillations much earlier at lower grid impedance than in the case of P-V control due to the manifestation of interaction in active power and voltage control. Consequently, the stability margin is reduced with such control under weak grid conditions.

For all cases with DVC-Q control (Figure 15j–l), it is characteristic that, regardless of the PLL bandwidth, instability is observed at a value of $L_g \approx 0.5$ pu, as in the case of P-Q control (Figure 15d–f). When $bw_{PLL} = 13$ Hz (Figure 15j), similar to Figure 15d, an aperiodic instability occurs because one root of the pair $\lambda_{11,12}$ of the outer active power control loop is in the right half-plane on the real axis. However, when the PLL bandwidth is increased to 30 Hz (Figure 15k), it can be seen that the instability has an oscillatory nature, and the cause is already a pair of conjugate roots $\lambda_{7,8}$ associated with the LPF of the voltage feedforward. This mechanism of oscillation occurrence coincides with the general trend identified in Section 3.5, and differs from the P-Q control case. At the same time, when the PLL bandwidth is reduced to 5 Hz (Figure 15l), the instability occurs again due to the pair of roots $\lambda_{11,12}$ of the outer active power control loop, which is expressed as an oscillatory instability at $L_g = 0.495$ pu. At further increase of the grid impedance ($L_g = 0.5$ pu) aperiodic instability will occur, which is clearly seen from the presented root locus. As a result, the considered DVC-Q control method has quite similar nature and moments of instability to the case of P-Q control except for the case with the increased bandwidth of PLL.

The presented results confirm that the obtained analytical conclusions about the mechanism of oscillation occurrence using simplified models are correct. However, the results obtained with the help of a detailed state-space model coincide quantitatively better with the simplified models in which the dynamics of the PLL controller are taken into account. Only in this case is it possible to avoid obtaining both excessively negative and positive conclusions about the stability of the grid inverter in a wide range of operating conditions.

It is worth noting an important point related to the occurrence of oscillations due to the interaction between the fast PLL controller and the dynamics of the weak grid. In Section 3.5, it was noted that theoretically the outer control loops can be involved in this mechanism of oscillations when their response rate is close to the PLL and grid dynamics. However, such interaction has not been identified before. Therefore, using a state-space model, the impact of tuning the control loops in the case of P-V inverter control on its stable operation under ultra-weak grid conditions is additionally considered. As was shown earlier in Figure 15a, with P-V control and initial PLL bandwidth ($bw_{PLL} = 13$ Hz), in the case of $L_g \approx 0.9$ pu, an oscillatory instability is observed due to the location of a pair of conjugate roots $\lambda_{11,12}$ of the outer control loops in the right half-plane (Case 1 in Figure 16).

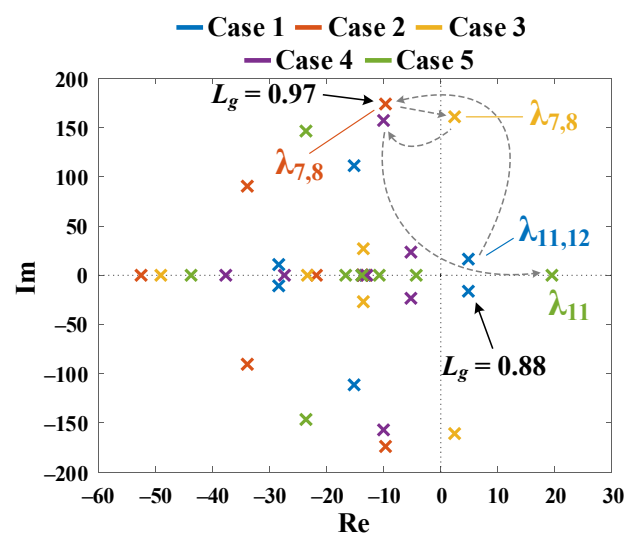


Figure 16. Root loci in the case of P-V control when changing the parameters of the control loops and the inverter load.

Increasing the response rate of the voltage controller ($K_{PV} = 1$ and $K_{IV} = 100$) makes it possible to exclude the occurrence of instability under ultra-weak grid conditions and to achieve the value of $SCR \approx 1$ (Case 2 in Figure 16), which can be seen from the location of all roots in the left half-plane at $L_g = 0.97$ pu. This fact confirms the conclusions made earlier in Section 3.1. It is very important that in the above cases, the full-load inverter is considered ($i_{od} = 1$ pu). If the inverter load is reduced, which is relevant due to the stochastic nature of renewables, the instability is observed again (Case 3 in Figure 16). The frequency of oscillation is 25.6 Hz. However, all the previous conclusions in Section 3 pointed out the opposite that decreasing the inverter load should increase the stability margin. Thus, this case is fundamentally different from the oscillation mechanisms discussed earlier. The cause of instability was the conjugate roots $\lambda_{7,8}$, corresponding to the LPF and entering the right half-plane. In order to ensure stable operation of the grid inverter at its low load, it is necessary to reduce the PLL bandwidth, e.g., to 8 Hz with $K_{P,PLL} = 25$ and $K_{I,PLL} = 820$ (Case 4 in Figure 16). However, when the inverter load is increased again and the PLL bandwidth is retained low, instability is observed (Case 5 in Figure 16)—the root λ_{11} of the outer active power control loop has a positive real part and lies on the real axis. Thus, when the inverter load decreases, a new mechanism of oscillation occurrence is manifested, the cause of which is the Interaction of outer controllers and PLL, which are comparable in response rate, under weak grid conditions. It is possible to increase the stability margin in this case by reducing the response rate of PLL and outer controllers, but this tuning is not appropriate when the inverter load increases. As a result, there is no possibility to use the same settings of controllers for different operating conditions of the grid inverter.

4.2. Simulation Verification and Analysis of Oscillation Spectrum

In order to verify the conclusions obtained from the detailed analytical model of the grid inverter with different control methods, the time-domain simulation of the detailed mathematical model of the three-phase two-level power converter, its control system and three-phase electric network using the PSCAD software is performed. Figure 17 shows waveforms of the output active power and three-phase current of the inverter for cases of P-V and P-Q control at different PLL bandwidth changes in the grid impedance leading to instability. This will allow adequately assessing the validity of the conclusions obtained using the analytical models of the system.

It can be seen from Figure 17a,b that when the detailed three-phase inverter model in the time-domain is considered with P-V control, instability occurs at grid impedances L_g similar to the values obtained using the detailed analytical model (Figure 15a,b). In this case, it is observed exactly oscillatory instability with oscillation frequencies of about 2.7 Hz for $bw_{PLL} = 13$ Hz and 23.4 Hz for $bw_{PLL} = 30$ Hz, which coincides with the frequencies of the roots entering the instability region in Figure 15a,b. When the inverter control is changed to P-Q control, an aperiodic instability is clearly observed at $L_g = 0.51$ pu (Figure 17c). This confirms the conclusions obtained earlier in Section 4.1 for a similar case (Figure 15d).

Figure 17d shows the case described at the end of Section 4.1 for P-V control with increasing response rate of the outer voltage control loop, which achieves stable operation of the grid inverter under ultra-weak grid conditions at full load (see the waveforms up to the moment of disturbance at 10 s). For the detailed three-phase model of the inverter, the permissible value of L_g before instability is 0.92 pu, which is only 5% less than the value for the analytical model. Furthermore, as a result of the reduction in the output power of the grid inverter, an instability with a frequency of oscillation of about 27.1 Hz is observed, which again confirms the conclusions drawn in Section 4.1. In the same way, results were obtained for DVC-V and DVC-Q control, which confirmed the nature of the processes and instability shown in Figure 15g–i.

Furthermore, using the obtained waveforms of three-phase currents shown in Figure 17 for different cases, the spectrum of occurring oscillations was assessed using the discrete Fourier transformation (Figure 18) [36].

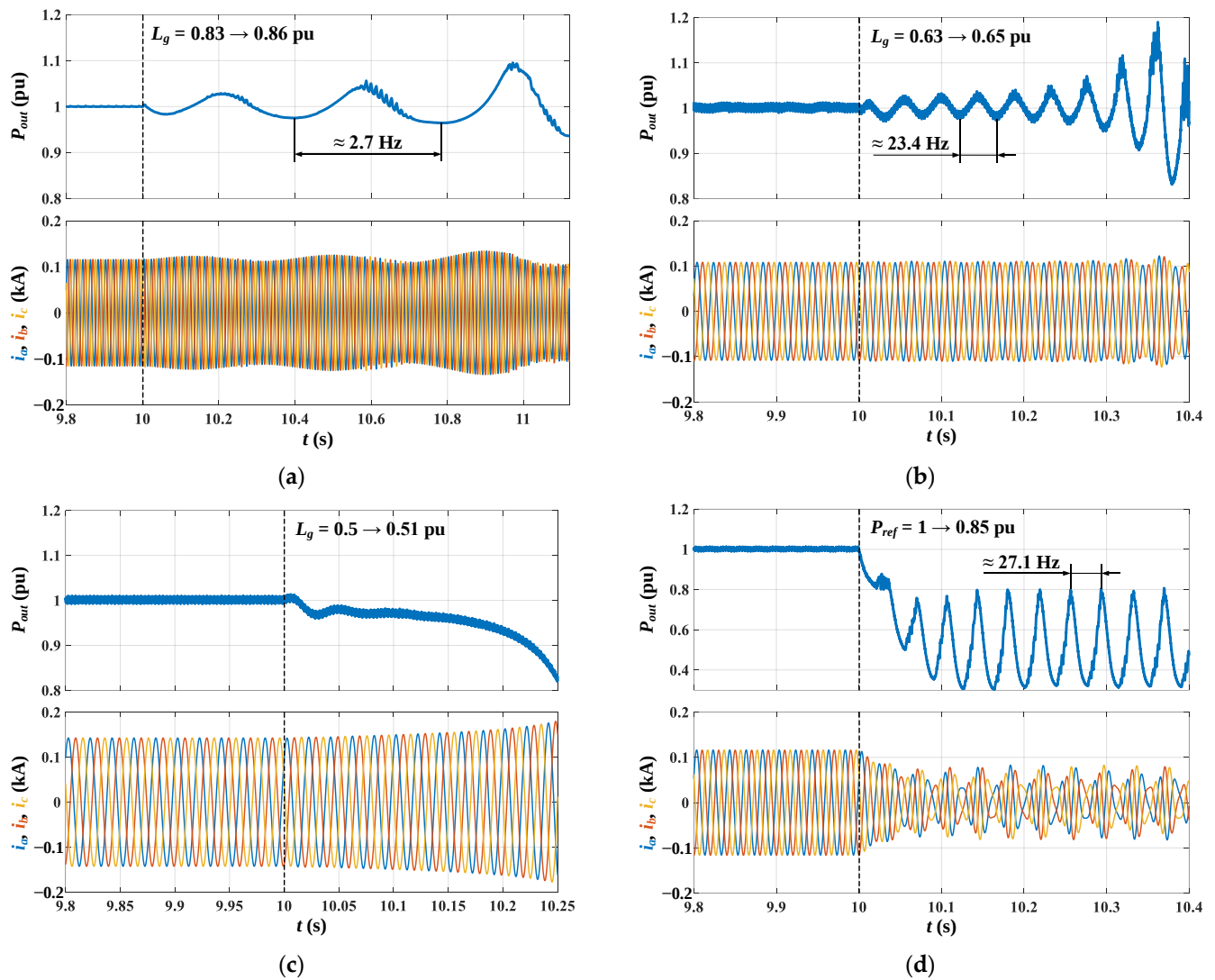


Figure 17. Waveforms obtained using detailed modeling: (a) P-V control with $bw_{PLL} = 13$ Hz and increasing L_g , (b) P-V control with $bw_{PLL} = 30$ Hz and increasing L_g , (c) P-Q control with $bw_{PLL} = 13$ Hz and increasing L_g , (d) P-V control with decreasing P_{ref} .

All the previously shown oscillation frequencies obtained by analyzing the detailed analytical model are related to the dq synchronous reference frame. The oscillations of active and reactive power of the grid inverter have the same frequency (Figure 17). If the discrete Fourier transformation is applied to the phase A current (Figure 18a) with P-V control, the dominant frequencies are 47.2 Hz and 52.8 Hz. These frequencies are already related to the abc stationary reference frame and are mirrored with respect to the fundamental frequency. These frequencies differ from fundamental by the value obtained in the synchronous reference frame (2.88 Hz in Figure 15a): $50 - 2.88 = 47.12$ Hz and $50 + 2.88 = 52.88$ Hz. As can be seen, the obtained values of oscillation frequencies using Fourier analysis and the analytical model are quite similar—the difference is not more than 1%. Similar dependences were obtained for other conditions (Figure 18b,c). At the same time, the mirror arrangement of the frequencies of the occurring oscillations proves that they are related exactly to the control system of the grid inverter, which are controlled in the dq reference frame [8,53].

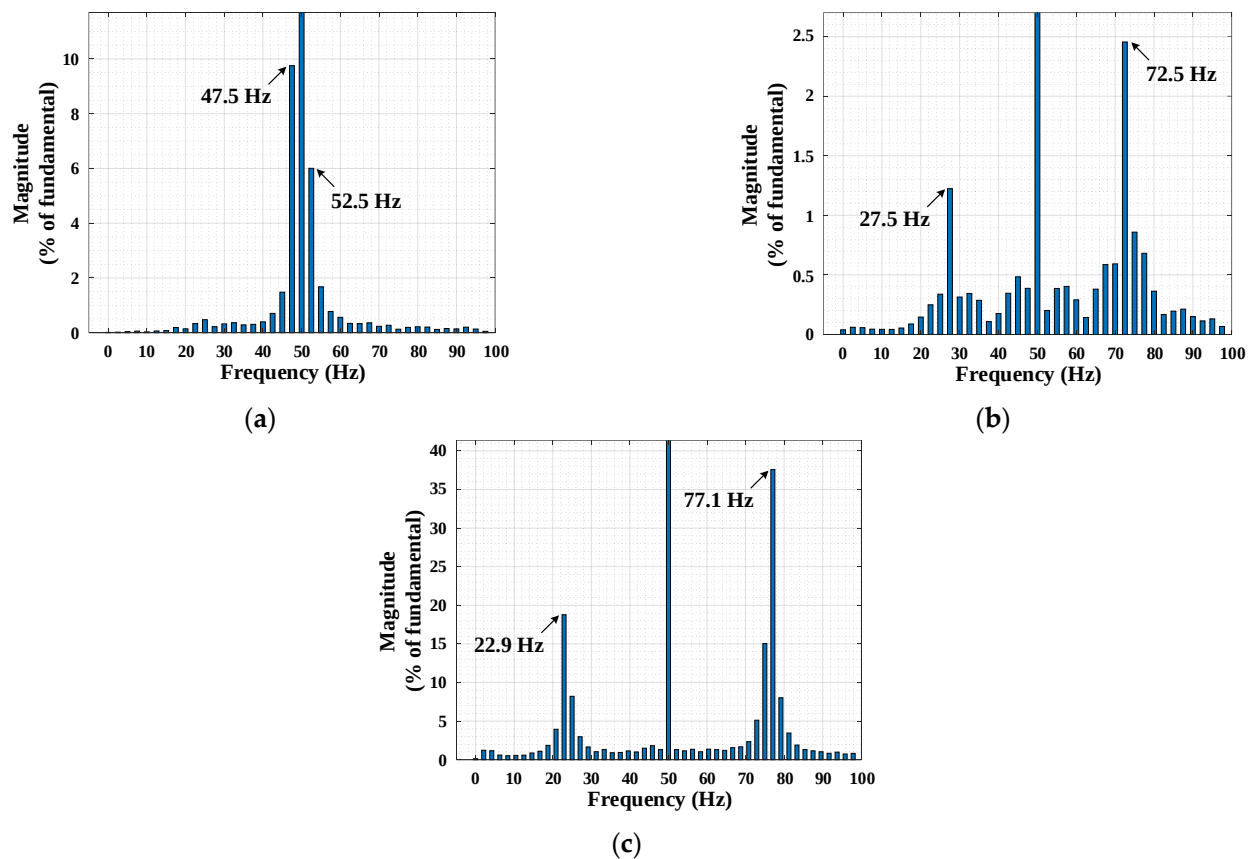


Figure 18. Harmonic spectrum for phase A current after the oscillation occurrence in case of P-V control: (a) $bw_{PLL} = 13$ Hz, (b) $bw_{PLL} = 30$ Hz, (c) with decreasing P_{ref} .

5. Experimental Verification

For further assessment of the obtained mechanisms and causes of oscillations, experimental studies were carried out by a control hardware-in-the-loop testing of the grid inverter using the RTDS (Figure 19). The RTDS rack is equipped with four PB5 processor cards and necessary input/output cards. Signal measurement was taken with a four-channel, 100 MHz bandwidth Rigol MSO4014 oscilloscope (Rigol, Beijing, China). The control system of the grid inverter with different control methods was coded into STM32H743ZI industrial microcontroller (STMicroelectronics, Geneva, Switzerland), which was used to control the digital model of the inverter in RTDS in real time. The test scheme with a grid-following inverter (Figure 1) is modelled in RTDS, with the electrical control part for the inverter implemented in STM32 microcontroller. The input of the microcontroller receives instantaneous values of three-phase currents and voltages through digital-to-analog converters of specialized RTDS cards. The output of the microcontroller generates PWM signals to control the digital model of the inverter. For verification, the cases that have been presented in detail in Section 4.2 are studied. The obtained waveforms of the inverter output active power and phase A current used in analog form by the microcontroller are shown in Figure 20. The output active power of the digital inverter model was measured on a microcontroller, where it is calculated based on instantaneous power theory, by providing a signal output to an integrated digit-to-analog converter.

Figure 20a shows the case for P-V control of the inverter with $bw_{PLL} = 13$ Hz during instability as a result of increasing the grid impedance L_g up to 0.85 pu, similar to Figure 17a. It is shown that increasing the response speed of the outer voltage controller helps to prevent the occurrence of oscillations of about 2.7 Hz with increasing magnitude. The latter ensures the stability of the grid inverter under ultra-weak grid conditions. Furthermore, it follows from Figure 20b that the obtained conclusion is valid under full-load inverter, since

oscillations with a frequency of 27 Hz occur in the case of a decrease in the output power. In order to ensure stability in this case, it is possible to reduce the PLL bandwidth, which is confirmed by the waveforms in Figure 20b.

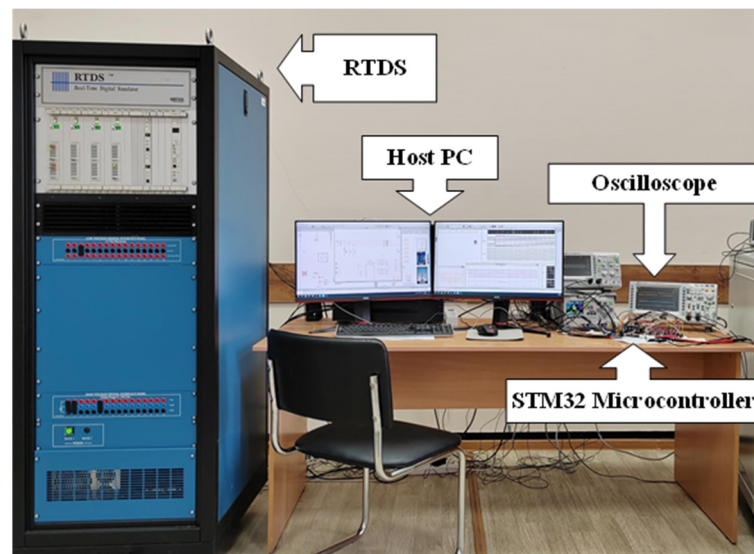
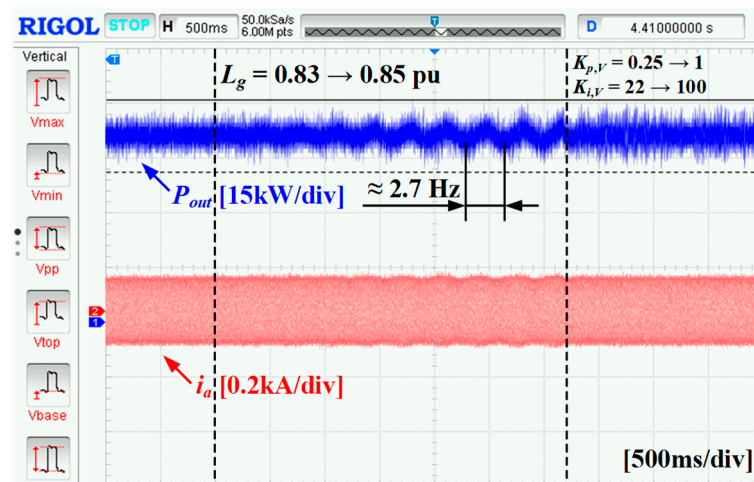
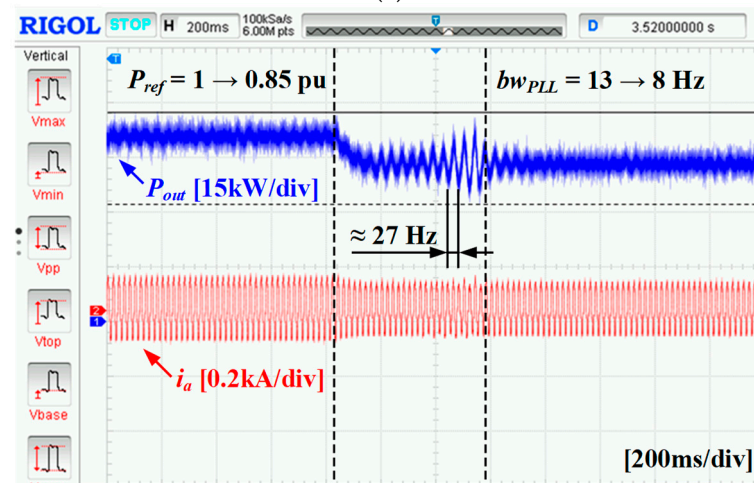


Figure 19. Experimental setup for closed-loop testing.



(a)



(b)

Figure 20. Cont.

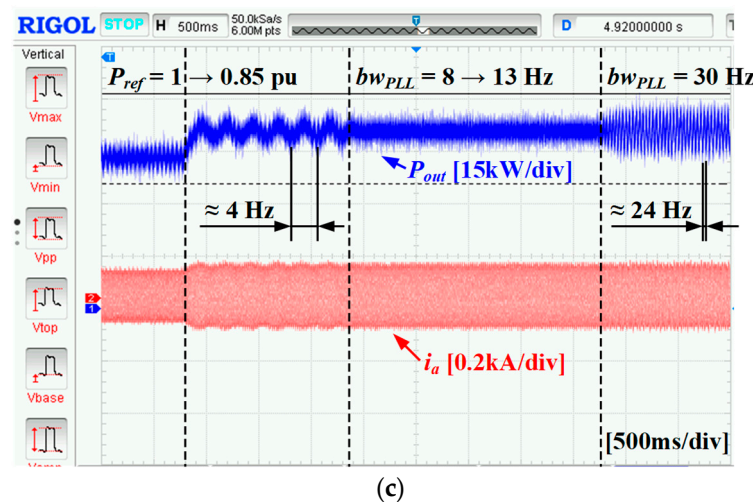


Figure 20. Experimental results obtained during closed-loop testing in the case of P-V inverter control: (a) with $bw_{PLL} = 13$ Hz and increasing L_g , and then changing the parameters of the voltage controller, (b) with decreasing P_{ref} and PLL bandwidth, (c) with $bw_{PLL} = 13$ Hz and increasing P_{ref} , and then increasing PLL bandwidth.

However, at low bandwidth of PLL and increasing the output power (Figure 20c), the occurrence of undamped oscillations with a frequency of about 4 Hz is again observed. Earlier in Figure 16 it was shown that the instability in this case occurs because the root of the outer control loop is located in the right half-plane. Thus, the instability of such tuning parameters of the control system is satisfied. At the same time, as the closed-loop testing shows, at first there will be an oscillatory instability due to the PLL operation with subsequent aperiodic instability. To maintain stability, it is possible to increase the PLL bandwidth back to $bw_{PLL} = 13$ Hz (Figure 20c). It is worth noting that at an excessive increase of the PLL bandwidth, e.g., to $bw_{PLL} = 30$ Hz, instability will be observed, as shown at the end of the waveforms in Figure 20c, where the frequency of occurring oscillations is about 24 Hz, which corresponds to the conclusions obtained from Figure 17b. In summary, the experimental results obtained confirmed the previous conclusions based on the simplified and detailed models of the grid inverter.

6. Summary of Research Results and Classification of SSO Occurrence Mechanisms

Based on the results of the research, a summary table reflecting the mechanisms of SSO occurrence and their features was formed (Table 4). The major cause leading to the occurrence of SSO is the weak grid conditions. The impact of inverter load has a non-directional effect. In most cases, increasing the load also increases the probability of oscillation occurrence. However, when the response rate of outer control loops, such as a voltage controller, becomes comparable to the PLL controller, their interaction will lead to the SSO occurrence already when the inverter output active power is reduced. Another cause of oscillations is the PLL itself. The nature of oscillations depends on the PLL bandwidth. At high bandwidth, oscillations are associated with possible delays in signal processing and filtering. At a rather slow PLL operation, the oscillations are caused by the lack of damping properties due to inappropriate settings for the current operating conditions. This specific characteristic of the SSO due to the PLL operation is manifested for most control types: P-V, DVC-V and DVC-Q. The only exception is P-Q control, in which SSOs do not occur because aperiodic instability occurs much earlier due to reaching the limit of network power transfer capability. At the same time, in the case of maintaining the voltage level in the network at the expense of external sources, SSO may occur due to the high-speed PLL. It is worth noting the DC-link voltage controller (DCVC in Table 4), the inappropriate tuning of which leads to oscillatory instability in most cases. In addition,

SSOs occur due to the interaction of active power controller (APC in Table 4) and voltage controller (VC in Table 4), even in case of an appropriate tuning of each of them.

Table 4. Classification of SSO occurrence mechanisms related to the inverter control system.

Control	Conditions	P-V Control			P-Q Control				DVC-V Control			DVC-Q Control			
		bw _{PLL}			bw _{VC}	bw _{PLL}			bw _{PLL}			bw _{VC}	bw _{PLL}		
		High	Med.	Low	High	High	Med.	Low	High	Med.	Low	High	High	Med.	Low
Operating conditions	L_g	Increase ↑													
	i_{od}	↑	↑	↑	↓	↑	↑	↑	↑	↑	↑	↓	↑	↑	↑
	U_o	Decrease ↓													
Nature of instability		oscil.	oscil.	oscil.	oscil.	oscil./aperiod.	aperiod.	aperiod.	oscil.	oscil.	oscil.	oscil.	oscil.	aperiod.	oscil.
Mirrored frequency		yes	yes	yes	yes	yes/no	no	no	yes	yes	yes	yes	yes	no	yes
SSO frequency in dq frame, Hz		≈25.3	≈2.8	≈1.96	≈25.6	≈27/–	–	–	≈26	≈4	≈3	≈24	≈27	–	≈1.3
Cause of SSO		De-lays	APC and VC interaction	PLL tuning	PLL and VC interaction	Delays/N.A. (power transfer limits)	N.A. (power transfer limits)	N.A. (power transfer limits)	De-lays	DCVC tuning	PLL tuning	PLL and VC interaction	De-lays	DCVC tuning	DCVC tuning

↑ indicates an increase in the parameter, ↓ indicates a decrease in the parameter.

The distinctive features of the occurring oscillations are their wide frequency spectrum, which, according to the experimental results, ranged from a few Hz to values close to the synchronous frequency. The second feature is the presence of two mirrored frequencies of oscillations in three-phase variables with respect to the synchronous frequency. Moreover, this feature can be found for all mechanisms and can reasonably be considered as one of the main criteria indicating the SSO occurrence due to the inverter control system under certain operating conditions of the external grid.

7. Conclusions

This paper presents the results of analyzing simplified and detailed models of the grid inverter taking into account different approaches to active and reactive power control. The considered sequence of models with their increasing complexity allowed to identify specific control loops that lead to the SSOs occurrence and factors that increase the probability of oscillations.

As a result, five different mechanisms of SSO occurrence were identified from the various simplified models. Moreover, using the developed detailed state–space model it was possible not only to verify the results obtained using simplified transfer functions, but also to identify an additional sixth mechanism of SSO occurrence.

As a result, on the basis of frequency analysis, time–domain mathematical modeling and closed-loop testing, this paper classifies the mechanisms of SSO occurrence related to the dynamics of the grid inverter control system under various operating conditions. The classification is based on the division of mechanisms according to the applied controllers and the PLL bandwidth, different combinations of which determine the mechanism of SSO occurrence. Three PLL bandwidths and four controllers are considered. In addition, the inverter operating conditions have a significant impact, which can lead to different mechanisms of SSO occurrence. Among the latter are the grid strength, the inverter load and the grid voltage.

The distinctive feature of the SSOs considered in this paper, which are related to the control system of the grid inverter, is the wide frequency range (from low-frequency oscillations up to synchronous frequency), as well as the mirror arrangement of oscillation frequencies for three-phase variables. Thus, it has been proven that the mechanisms of oscillations are various. At the same time, it is currently quite difficult to form universal quantitative indicators that would signal the occurrence of oscillations and serve as their indicators in practice. For this purpose, further research and experimental studies will

be performed. In addition, further research should consider the impact of plant-level controllers on the mechanism of SSO occurrence.

Author Contributions: Conceptualization, A.A.; Methodology, A.A. and A.S.; Formal analysis, P.I.; Software, A.A. and Y.B.; Investigation, P.R.; Validation, Y.B. and P.R.; Resources, R.U.; Supervision, P.I. and A.S.; Funding acquisition, A.S.; Writing—original draft, A.A. and A.S.; Writing—review & editing, R.U. and P.I. All authors have read and agreed to the published version of the manuscript.

Funding: The reported study was funded by the Russian Science Foundation, project number 24-29-00004.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Grid and inverter parameters.

Parameter	Value	Parameter	Value	Parameter	Value
U_b , V	400	L_g , pu	0.2	K_{PP} , pu	0.2
S_b , kW	50	K_{ff} , pu	1	K_{IP} , pu/s	27
f_b , Hz	50	T_{ff} , s	0.001	C_{dc} , uF	3200
f_{sw} , kHz	4	K_{PC} , pu	0.15	$U_{b,dc}$, V	800
L_f , mH	1.53	K_{IC} , pu/s	2.07	K_{PV} , pu	0.25
C_f , uF	75.2	$K_{P,PLL}$, pu	0.191	K_{IV} , pu/s	22
R_g , pu	0.001	$K_{I,PLL}$, pu/s	4.4563	I_{max} , pu	1.2

References

- Zhang, G.; Li, Z.; Zhang, B.; Halang, W.A. Power Electronics Converters: Past, Present and Future. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2028–2044. [\[CrossRef\]](#)
- Strielkowski, W.; Civi, L.; Tarkhanova, E.; Tvaronavičienė, M.; Petrenko, Y. Renewable Energy in the Sustainable Development of Electrical Power Sector: A Review. *Energies* **2021**, *14*, 8240. [\[CrossRef\]](#)
- Askarov, A.; Rudnik, V.; Ruban, N.; Radko, P.; Ilyushin, P.; Suvorov, A. Enhanced Virtual Synchronous Generator with Angular Frequency Deviation Feedforward and Energy Recovery Control for Energy Storage System. *Mathematics* **2024**, *12*, 2691. [\[CrossRef\]](#)
- Prasanthi, L.; Panigrahy, A.K.; Durga Prakash, M. An Organic Thin-Film Transistors (OTFTs) with Steep Subthreshold and Ultra-Low Temperature Solution Processing for Label-Free Biosensing. *IEEE Access* **2024**, *12*, 172851–172866. [\[CrossRef\]](#)
- Mounika, B.; Panigrahy, A.K.; Ajayan, J.; Khadar Basha, N.; Bharath Sreenivasulu, V.; Durga Prakash, M.; Bhattacharya, S.; Nirmal, D. A Novel LG = 40 Nm AlN-GDC-HEMT on SiC Wafer with ft/IDS, Peak of 400 GHz/3.18 mA/Mm for Future RF Power Amplifiers. *IEEE Access* **2024**, *12*, 131906–131914. [\[CrossRef\]](#)
- Hatziaargyriou, N.; Milanovic, J.; Rahmann, C.; Ajarapu, V.; Canizares, C.; Erlich, I.; Hill, D.; Hiskens, I.; Kamwa, I.; Pal, B.; et al. Definition and Classification of Power System Stability—Revisited & Extended. *IEEE Trans. Power Syst.* **2021**, *36*, 3271–3281. [\[CrossRef\]](#)
- Ilyushin, P.; Volnyi, V.; Suslov, K.; Filippov, S. Review of Methods for Addressing Challenging Issues in the Operation of Protection Devices in Microgrids with Voltages of up to 1 kV That Integrates Distributed Energy Resources. *Energies* **2022**, *15*, 9186. [\[CrossRef\]](#)
- Cheng, Y.; Fan, L.; Rose, J.; Huang, S.-H.; Schmall, J.; Wang, X.; Xie, X.; Shair, J.; Ramamurthy, J.R.; Modi, N.; et al. Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources. *IEEE Trans. Power Syst.* **2023**, *38*, 316–330. [\[CrossRef\]](#)
- Xie, X.; Shair, J. Introduction to Power System Oscillatory Stability. In *Oscillatory Stability of Converter-Dominated Power Systems*; Power Systems; Springer: Cham, Switzerland, 2024. [\[CrossRef\]](#)
- Shair, J.; Xie, X.; Wang, L.; Liu, W.; He, J.; Liu, H. Overview of Emerging Subsynchronous Oscillations in Practical Wind Power Systems. *Renew. Sustain. Energy Rev.* **2019**, *99*, 159–168. [\[CrossRef\]](#)
- Rudnik, V.E.; Askarov, A.B.; Malyuta, B.D.; Ufa, R.A.; Suvorov, A.A. Analysis of Subsynchronous Oscillations Simulations by Generic Model of PV and Hydrogen Systems in Bulk Power System. *Int. J. Hydrogen Energy* **2024**, *86*, 1299–1309. [\[CrossRef\]](#)
- Xie, X.; Shair, J.; Beerten, J.; Fan, L.; Gomis-Bellmunt, O.; Vorobev, P.; Preece, R.; Shah, S.; Wang, X.; Wang, Y.; et al. Guest Editorial: Control Interactions in Power Electronic Converter Dominated Power Systems. *Int. J. Electr. Power Energy Syst.* **2024**, *155*, 109553. [\[CrossRef\]](#)

13. Ilyushin, P.; Filippov, S.; Kulikov, A.; Suslov, K.; Karamov, D. Intelligent Control of the Energy Storage System for Reliable Operation of Gas-Fired Reciprocating Engine Plants in Systems of Power Supply to Industrial Facilities. *Energies* **2022**, *15*, 6333. [\[CrossRef\]](#)
14. Badrzadeh, B.; Fan, L.; Modi, N.; Haddadi, A. Power System Dynamic Studies Under a High Penetration of Power Electronic-Interfaced Devices. In *Power System Dynamic Modelling and Analysis in Evolving Networks*; CIGRE Green Books; Springer: Cham, Switzerland, 2024. [\[CrossRef\]](#)
15. Yu, L.; Meng, K.; Zhang, W.; Dong, J.; Nadarajah, M. System Strength Challenges: An Overview of Energy Transition in Australia's National Electricity Market. In Proceedings of the 2021 IEEE 4th International Electrical and Energy Conference (CIEEC), Wuhan, China, 28–30 May 2021; pp. 1–6. [\[CrossRef\]](#)
16. Fan, L.; Miao, Z.; Shah, S.; Cheng, Y.; Rose, J.; Huang, S.-H.; Pal, B.; Xie, X.; Modi, N.; Wang, S.; et al. Real-World 20-Hz IBR Subsynchronous Oscillations: Signatures and Mechanism Analysis. *IEEE Trans. Energy Convers.* **2022**, *37*, 2863–2873. [\[CrossRef\]](#)
17. Zhou, J.Z.; Ding, H.; Fan, S.; Zhang, Y.; Gole, A.M. Impact of Short-Circuit Ratio and Phase-Locked-Loop Parameters on the Small-Signal Behavior of a VSC-HVDC Converter. *IEEE Trans. Power Deliv.* **2014**, *29*, 2287–2296. [\[CrossRef\]](#)
18. Yuan, H.; Yuan, X.; Hu, J. Modeling of Grid-Connected VSCs for Power System Small-Signal Stability Analysis in DC-Link Voltage Control Timescale. *IEEE Trans. Power Syst.* **2017**, *32*, 3981–3991. [\[CrossRef\]](#)
19. Zhao, M.; Yuan, X.; Hu, J.; Yan, Y. Voltage Dynamics of Current Control Time-Scale in a VSC-Connected Weak Grid. *IEEE Trans. Power Syst.* **2016**, *31*, 2925–2937. [\[CrossRef\]](#)
20. Strachan, N.P.W.; Jovcic, D. Stability of a Variable-Speed Permanent Magnet Wind Generator with Weak AC Grids. *IEEE Trans. Power Deliv.* **2010**, *25*, 2779–2788. [\[CrossRef\]](#)
21. Zhou, Y.; Nguyen, D.D.; Kjær, P.C.; Saylor, S. Connecting Wind Power Plant with Weak Grid—Challenges and Solutions. In Proceedings of the 2013 IEEE Power & Energy Society General Meeting, Vancouver, BC, Canada, 21–25 July 2013; pp. 1–7. [\[CrossRef\]](#)
22. Huang, Y.; Wang, D. Effect of Control-Loops Interactions on Power Stability Limits of VSC Integrated to AC System. *IEEE Trans. Power Deliv.* **2018**, *33*, 301–310. [\[CrossRef\]](#)
23. Hu, J.; Hu, Q.; Wang, B.; Tang, H.; Chi, Y. Small Signal Instability of PLL-Synchronized Type-4 Wind Turbines Connected to High-Impedance AC Grid During LVRT. *IEEE Trans. Energy Convers.* **2016**, *31*, 1676–1687. [\[CrossRef\]](#)
24. Fan, L.; Miao, Z. An Explanation of Oscillations Due to Wind Power Plants Weak Grid Interconnection. *IEEE Trans. Sustain. Energy* **2018**, *9*, 488–490. [\[CrossRef\]](#)
25. Huang, S.-H.; Schmall, J.; Conto, J.; Adams, J.; Zhang, Y.; Carter, C. Voltage Control Challenges on Weak Grids with High Penetration of Wind Generation: ERCOT Experience. In Proceedings of the 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012; pp. 1–7. [\[CrossRef\]](#)
26. Bao, L.; Fan, L.; Miao, Z.; Wang, Z. Hardware Demonstration of Weak Grid Oscillations in Grid-Following Converters. In Proceedings of the 2021 North American Power Symposium (NAPS), College Station, TX, USA, 14–16 November 2021; pp. 1–6. [\[CrossRef\]](#)
27. Papangelis, L.; Debry, M.-S.; Prevost, T.; Panciatici, P.; Van Cutsem, T. Stability of a Voltage Source Converter Subject to Decrease of Short-Circuit Capacity: A Case Study. In Proceedings of the 2018 Power Systems Computation Conference (PSCC), Dublin, Ireland, 11–15 June 2018; pp. 1–7. [\[CrossRef\]](#)
28. Fan, L. Modeling Type-4 Wind in Weak Grids. *IEEE Trans. Sustain. Energy* **2019**, *10*, 853–864. [\[CrossRef\]](#)
29. Alawasa, K.M.; Mohamed, Y.A.-R.I.; Xu, W. Modeling, Analysis, and Suppression of the Impact of Full-Scale Wind-Power Converters on Subsynchronous Damping. *IEEE Syst. J.* **2013**, *7*, 700–712. [\[CrossRef\]](#)
30. Liu, H.; Xie, X.; He, J.; Xu, T.; Yu, Z.; Wang, C.; Zhang, C. Subsynchronous Interaction Between Direct-Drive PMSG Based Wind Farms and Weak AC Networks. *IEEE Trans. Power Syst.* **2017**, *32*, 4708–4720. [\[CrossRef\]](#)
31. Li, Y.; Fan, L.; Miao, Z. Wind in Weak Grids: Low-Frequency Oscillations, Subsynchronous Oscillations, and Torsional Interactions. *IEEE Trans. Power Syst.* **2020**, *35*, 109–118. [\[CrossRef\]](#)
32. Hu, J.; Huang, Y.; Wang, D.; Yuan, H.; Yuan, X. Modeling of Grid-Connected DFIG-Based Wind Turbines for DC-Link Voltage Stability Analysis. *IEEE Trans. Sustain. Energy* **2015**, *6*, 1325–1336. [\[CrossRef\]](#)
33. Hu, J.; Wang, B.; Wang, W.; Tang, H.; Chi, Y.; Hu, Q. Small Signal Dynamics of DFIG-Based Wind Turbines During Riding Through Symmetrical Faults in Weak AC Grid. *IEEE Trans. Energy Convers.* **2017**, *32*, 720–730. [\[CrossRef\]](#)
34. Göksu, Ö.; Teodorescu, R.; Bak, C.L.; Iov, F.; Kjær, P.C. Instability of Wind Turbine Converters During Current Injection to Low Voltage Grid Faults and PLL Frequency Based Stability Solution. *IEEE Trans. Power Syst.* **2014**, *29*, 1683–1691. [\[CrossRef\]](#)
35. Dong, D.; Wen, B.; Boroyevich, D.; Mattavelli, P.; Xue, Y. Analysis of Phase-Locked Loop Low-Frequency Stability in Three-Phase Grid-Connected Power Converters Considering Impedance Interactions. *IEEE Trans. Ind. Electron.* **2015**, *62*, 310–321. [\[CrossRef\]](#)
36. Li, G.; Pan, H.; Liu, X.; Yin, L.; Hwang Goh, H. PLL Phase Margin Design and Analysis for Mitigating Sub/Super-Synchronous Oscillation of Grid-Connected Inverter under Weak Grid. *Int. J. Electr. Power Energy Syst.* **2023**, *151*, 109124. [\[CrossRef\]](#)
37. Li, G.; Bao, X.; Liu, X. A Double-Loop Inertia Phase-Locked Loop with Antidisturbance Ability. *IEEE Trans. Ind. Inform.* **2023**, *19*, 5585–5592. [\[CrossRef\]](#)
38. Wu, B.; Lang, Y.; Zargari, N.; Kouro, S. *Power Conversion and Control of Wind Energy Systems*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
39. Fan, L.; Miao, Z. *Modeling and Stability Analysis of Inverter-Based Resources*; CRC Press: Boca Raton, FL, USA, 2023.

40. Cortajarena, J.A.; Barambones, O.; Alkorta, P.; Cortajarena, J. Grid Frequency and Amplitude Control Using DFIG Wind Turbines in a Smart Grid. *Mathematics* **2021**, *9*, 143. [\[CrossRef\]](#)
41. Blaabjerg, F.; Teodorescu, R.; Liserre, M.; Timbus, A.V. Overview of Control and Grid Synchronization for Distributed Power Generation Systems. *IEEE Trans. Ind. Electron.* **2006**, *53*, 1398–1409. [\[CrossRef\]](#)
42. Suvorov, A.; Askarov, A.; Kievets, A.; Rudnik, V. A Comprehensive Assessment of the State-of-the-Art Virtual Synchronous Generator Models. *Electr. Power Syst. Res.* **2022**, *209*, 108054. [\[CrossRef\]](#)
43. Ali, Z.; Christofides, N.; Hadjidemetriou, L.; Kyriakides, E.; Yang, Y.; Blaabjerg, F. Three-Phase Phase-Locked Loop Synchronization Algorithms for Grid-Connected Renewable Energy Systems: A Review. *Renew. Sustain. Energy Rev.* **2018**, *90*, 434–452. [\[CrossRef\]](#)
44. Alturki, M.; Abbassi, R.; Albaker, A.; Jerbi, H. A New Hybrid Synchronization PLL Scheme for Interconnecting Renewable Energy Sources to an Abnormal Electric Grid. *Mathematics* **2022**, *10*, 1101. [\[CrossRef\]](#)
45. Anttila, S.; Döhler, J.S.; Oliveira, J.G.; Boström, C. Grid Forming Inverters: A Review of the State of the Art of Key Elements for Microgrid Operation. *Energies* **2022**, *15*, 5517. [\[CrossRef\]](#)
46. Baier, C.R.; Melin, P.E.; Torres, M.A.; Ramirez, R.O.; Muñoz, C.; Quinteros, A. Developing and Evaluating the Operating Region of a Grid-Connected Current Source Inverter from Its Mathematical Model. *Mathematics* **2024**, *12*, 1775. [\[CrossRef\]](#)
47. Yazdani, A.; Iravani, R. *Voltage-Sourced Converters in Power Systems: Modeling, Control, and Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2010.
48. Kundur, P.S. Power System Stability. In *Power System Stability and Control*; CRC Press: Boca Raton, FL, USA, 2012.
49. Fan, L. *Control and Dynamics in Power Systems and Microgrids*; CRC Press: Boca Raton, FL, USA, 2017. [\[CrossRef\]](#)
50. Wen, B.; Boroyevich, D.; Burgos, R.; Mattavelli, P.; Shen, Z. Analysis of D-Q Small-Signal Impedance of Grid-Tied Inverters. *IEEE Trans. Power Electron.* **2016**, *31*, 675–687. [\[CrossRef\]](#)
51. Suvorov, A.; Askarov, A.; Bay, Y.; Maliuta, B.; Achitaev, A.; Suslov, K. Comparative Small-Signal Stability Analysis of Voltage-Controlled and Enhanced Current-Controlled Virtual Synchronous Generators under Weak and Stiff Grid Conditions. *Int. J. Electr. Power Energy Syst.* **2023**, *147*, 108891. [\[CrossRef\]](#)
52. Askarov, A.; Ruban, N.; Bay, Y.; Ufa, R.; Malkova, Y.; Suvorov, A. A Feedforward Control for Increasing the Damping Effect of Enhanced Current-Controlled Virtual Synchronous Generator. *Electr. Power Syst. Res.* **2024**, *234*, 110659. [\[CrossRef\]](#)
53. Salehi, F.; Matsuo, I.B.M.; Brahman, A.; Tabrizi, M.A.; Lee, W.-J. Sub-Synchronous Control Interaction Detection: A Real-Time Application. *IEEE Trans. Power Deliv.* **2020**, *35*, 106–116. [\[CrossRef\]](#)

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