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Review

Enabling Technologies for Enhancing Power System Stability in the Presence of Converter-Interfaced Generators

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Abstract: The growing attention to environmental issues is leading to an increasing integration of renewable energy sources into electrical grids. This integration process could contribute to power system decarbonization, supporting the diversification of primary energy sources and enhancing the security of energy supply, which is threatened by the uncertain costs of conventional energy sources. Despite these environmental and economical benefits, many technological and regulatory problems should be fixed in order to significantly increase the level of penetration of renewable power generators, which are connected to power transmission and distribution systems via power electronic interfaces. Indeed, these converter-interfaced generators (CIGs) perturb grid operation, especially those fueled by non-programmable energy sources (e.g., wind and solar generators), affecting the system stability and making power systems more vulnerable to dynamic perturbations. To face these issues, the conventional operating procedures based on pre-defined system conditions, which are currently adopted in power system operation tools, should be enhanced in order to allow the "online" solution of complex decision-making problems, providing power system operators with the necessary measures and alerts to promptly adjust the system. A comprehensive analysis of the most promising research directions and the main enabling technologies for addressing this complex issue is presented in this paper.

Keywords: power system stability; frequency stability; rotor angle stability; voltage stability; power system inertia; converter-interfaced generation; renewable power generators

Citation: Giannuzzi, G.M.; Mostova, V.; Pisani, C.; Tessitore, S.; Vaccaro, A. Enabling Technologies for Enhancing Power System Stability in the Presence of Converter-Interfaced Generators. *Energies* **2022**, *15*, 8064. https://doi.org/10.3390/en15218064

Academic Editor: Abu-Siada Ahmed

Received: 29 September 2022
Accepted: 24 October 2022
Published: 30 October 2022

1. Introduction

The need for mitigating the effects of climate change, the progressive depletion of fossil resources, and the growing energy demand of developing countries has led to an exponential increase of renewable power generators connected to transmission and distribution grids by power electronic converters.

In particular, it is expected that the globally installed capacity of electricity generation from wind and photovoltaics generators will increase to about 3.8 TW by 2030 [1]. It is well known that the large scale penetration of these converter-interfaced generators (CIGs) in existing power grids requires major revisions of the conventional policies currently adopted for power system planning, operation, and regulation [2]. The importance of this revision process has been confirmed in many countries, where the rapid growth of grid-connected CIGs without defining and implementing proper corrective actions aimed at enhancing the grid flexibility, sensibly affected the power system stability and security.

Moreover, the modern technological advances pushed the pervasive integration of power electronic converters in both transmission and distribution power systems for enabling a wide range of applications, which are not only restricted to the grid connection of distributed generators. For example, in transmission systems, power converters are the technological backbone supporting flexible AC transmission systems (FACTS) and high voltage DC transmission systems (HVDC), while, in distribution networks, they are extensively deployed in microgrids and DC distribution networks. Finally, they are widely used in many end-user applications such as electric vehicles and variable frequency drives [3].

The technical impacts induced by the large-scale penetration of power electronic converters in modern power systems should be carefully analyzed, especially those related to CIGs, which in the medium/long term are expected to replace all the conventional synchronous generators (SG). In particular, the main features differentiating CIGs from SGs are the nominal power, which is extremely lower, the generator inertia, which is zero for static generators, the active power regulation, which is limited for renewable power generators, and the dynamic response, which is extremely faster [4]. These intrinsic differences reduce the grid flexibility, make power systems more vulnerable to dynamic perturbations, and sensibly increase the complexity of power system operation.

To address these critical issues, wide-area monitoring protection and control systems (WAMPACs) are being increasingly applied by transmission system operators worldwide for real-time power system monitoring and early detection of dynamic perturbations. WAMPACs involve the use of system-wide information to avoid large disturbances and reduce the probability of catastrophic events by supporting the application of adaptive protection and control strategies aimed at increasing network capacity and minimizing wide-area disturbances [5]. Moreover, based on measured data processing, online decision support systems have also been applied in the task of promptly identify mitigation actions aimed at protecting the power system, avoiding large blackouts. These solutions allow processing large sensor data-streaming, providing system operators with the necessary measures and alerts to adjust the system, i.e., reduce impacts of load and renewable power generation fluctuations, for example, due to intermittency. In addition, several indices have been proposed for real-time monitoring of the grid stability, whose estimation can greatly enhance the situational awareness of TSOs [6]. In this context, this paper, starting from a comprehensive classification of the main phenomena that could affect power system stability, analyzes the relevant research directions and the most promising technologies and methodologies aimed at enhancing the dynamic grid performance in the presence of a massive penetration of power converter-based distributed generators. Moreover, the concept of electrical system stability and its classification are properly revised in order to consider the potential effects deriving by the large-scale replacement of conventional synchronous generators with distributed renewable generation systems. In this context, particular emphasis is given to the analysis of the critical issues characterizing modern power systems, such as the inertia decrease and the vulnerability to dynamic perturbations over multiple time scales, and their potential impacts on power system stability, flexibility and resilience. Finally, the most promising enabling technologies for improving system stability are analyzed in details.

The rest of the paper is organized as follows: Section 2 defines and classifies the power system stability according to the modern approaches proposed in the literature. The main technical impacts and the most challenging issues induced by a large-scale pervasion of CIGs in power systems are discussed in Section 3. Section 4 is focused on the analysis of the impacts of CIGs on power system stability, and the review of the most promising mitigation technologies used by TSOs. The concluding remarks are summarized in Section 5.

2. Definition and Classification of Power System Stability

Power system stability is defined as "the ability of the system, for a given initial operating condition, to return to a state of operating equilibrium after a physical disturbance, with most of the variables of the system constrained so that the entire system remains intact" [7]. This definition highlights the ability of the system to withstand both minor disturbances, such as load variations and, more importantly, major disturbances such as the failure of a generator or a short circuit on a line, since these events entail significant structural changes with obvious effects on the stability of the system. Studies and constant analysis of the network are essential in order to implement appropriate planning measures. However, designing a power system that can withstand any single or multiple contingency, resulting as robust against any disturbance event, is technically and economically unfeasible. Hence, power system planning is often based on a proper trade-off between reliability and economy, considering only the events with the highest probability of occurrence and/or those inducing severe grid perturbations.

Hence, in order to analyze the dynamic events that could compromise the system stability, and develop effective strategies aimed at mitigating their effects, it is extremely important to rigorously classify the forms of stability considering various features such as the disturbance magnitude, the time dynamics, the involved devices, and, most importantly, the physical nature of the instability [7].

Recently, the stability classification has been revised and expanded in order to take into account the grid effects of CIGs. In particular, it has been introduced two additional categories to the three existing categories of rotor angle stability, frequency stability, and voltage stability, namely resonance stability and converter-driven stability. This enhancement was necessary because, in contrast to conventional generators, which are characterized by rather slow electromechanical phenomena, CIGs are characterized by much faster dynamics, ranging from a few microseconds to several milliseconds, inducing complex electromagnetic phenomena [8].

More details about this classification, which is schematically depicted in Figure 1, are discussed in the follow sub-sections.

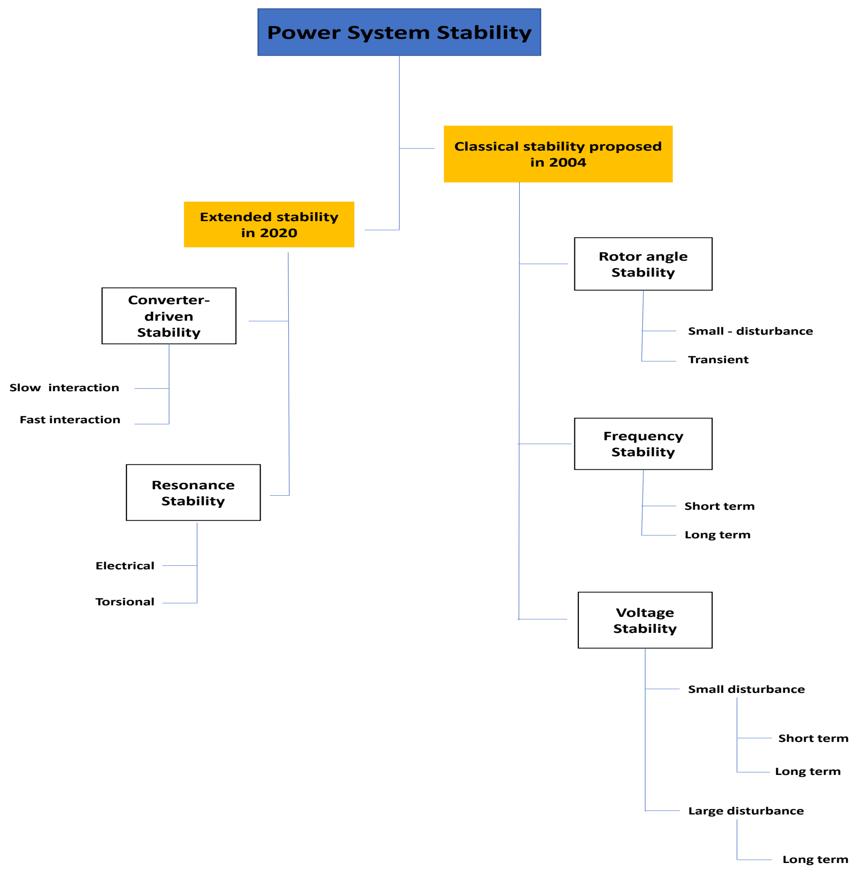

Figure 1. Power system stability classification (2004) and subsequent extension (2020) performed by the Task Force by the IEEE Power System Dynamic Performance Committee and the CIGRE Study Committee 38.

Rotor Angle Stability: The ability of the power system to maintain synchronism after a small disturbance (small-signal stability) or a large disturbance (transient stability). After a disturbance, there is an imbalance between mechanical and electromagnetic torque that causes the acceleration or deceleration of the generator rotors. This produces an angular difference that causes part of the load to be transferred from the slower machines to the faster machines, and if the system is unable to synchronize by absorbing kinetic energy, rotor angular instability occurs.

The change in electromagnetic torque can be divided into two components: a synchronisation torque in phase with the rotor angle deviation, whose absence causes non-oscillatory instability, and a damping torque in phase with the speed deviation, whose absence causes oscillatory instability. For the existence of a stability condition, the presence of both components is required for each synchronous machine.

Frequency Stability: The ability of the system to keep the frequency close to the nominal value after a large imbalance between generation and load. It is ensured by proper coordinating the control and protection devices, and can be classified into short-term and long-term frequency stability, depending on the timing of the event. Frequency stability is closely related to rotor angle stability, since rotor speed is related to grid frequency. It should also be taken into account that during frequency excursions, the voltage also fluctuates significantly, which can lead to untimely or poorly coordinated operation of the protection systems [9].

Voltage Stability: the ability of the power system to maintain voltage magnitudes at all buses as close as possible to the nominal value after a disturbance. Voltage instability induces a drop or rise in voltage at some buses, which can lead to cascading outages or load losses, and depends on the ability to maintain or restore the balance between load demand and supply [8]. Voltage stability can be divided into two subcategories: one considers the magnitude of the disturbance (voltage stability for small disturbances and voltage stability for large disturbances), while the other distinguishes the duration of instability (short-term voltage stability and long-term voltage stability). Voltage stability is highly load dependent, since after a disturbance the load on the high-voltage grid is increased with the aim of restoring power consumption beyond the capacity of the transmission and generation system. This leads to an increase in reactive power consumption, and consequently to an increase in voltage drop [10]. Although the most common form of voltage instability is related to voltage reduction, overvoltage instability could also be possible, and it is mainly caused by the network capacitance, which hinders the absorption of reactive power by synchronous compensators [11].

Resonance Stability: resonance occurs when energy exchange occurs in an oscillatory pattern; when oscillations exceed certain predetermined thresholds, there is a risk that resonance instability will occur. Depending on whether the resonance phenomenon manifests itself mechanically (torsion of the drive shaft) or electrically, a further subdivision is made [8].

(a) Torsional resonance: The resonance is due to torsional interactions between the series-compensated lines and the mechanical shaft of the turbine generator. The vibrations generated by the interaction between the fast-acting control devices and the system stabilizers can be poorly damped, undamped, or even negatively damped and increasing, threatening the mechanical integrity of the shaft.

(b) Electrical resonance: This resonance occurs in certain types of generators that have been found to be particularly susceptible to the phenomenon of self-excitation, in which the series-connected capacitor forms a resonant circuit with the actual inductance of the generator at sub-synchronous frequencies. The resonance results in both large currents and large voltage fluctuations that can be fatal to the electrical equipment of the generator, as well as to the transmission system.

Converter-Driven Stability: Unstable oscillations can occur in the system due to cross-couplings with the electromagnetic dynamics of the machines and electromagnetic transients in the network. The couplings are mainly due to the very fast dynamics of the converter controls on which the CIG is based. Depending on whether the interactions that occur are slow (less than 10 Hz) or fast (10 to hundreds of Hz), the phenomena can be further classified according to frequency levels [8] as follows:

(a) Stability of converters with fast interactions: interactions can cause oscillations at high/very high frequencies (hundreds of Hz to several kHz), a phenomenon called harmonic instability. An example of such instability is the controllers of synthetic inertial systems.
(b) Stability due to slow-response inverters: dynamic interactions involve control systems of power electronics devices with slow-response system components.

3. Grid Impacts of Large-Scale CIGs Penetration

The main feature characterizing power systems with high CIGs penetration is certainly the uncertainties induced by the intermittence of the renewable power generators, whose injected power profiles are not programmable and depend on the dynamics of the particular energy source (e.g., wind speed, solar radiation). Although these profiles can be predicted over different time horizons, these predictions are often affected by large forecasting errors, which raises the power system operation complexities [12].

Another remarkable feature of these power systems is the different time scales characterizing the system dynamics. While the dynamics of the conventional power systems settles in a range of 10^{-2} to 10^{3} s, the dynamics of the CIGs-based system goes down to 10^{-4} or 10^{-6} s by switching from electromechanical to electromagnetic dynamics [13]. This feature leads to undesirable dynamic coupling, which is much more likely in MV and LV networks characterized by a high R/X ratio.

Systems with high CIGs penetration also have a low tolerance to frequency and voltage deviations. For example, the limits of a wind generator are far lower than those of a conventional generator (50.2 Hz versus 51.5 Hz for frequency and 1.1 p.u. versus 1.3 p.u. for voltage), which could trigger frequent grid disconnections, and dynamic perturbation phenomena [14]. Moreover, these generators are characterized by low inertia and low short-circuit current. In particular, the low inertia is due to the presence of the converter, which decouples the frequency from the grid and no longer has the characteristics of traditional frequency response based on rotational kinetic energy. Low system inertia, especially at the regional level, causes very rapid and high amplitude frequency deviations with the resulting risk of cascading events [15]. The low short-circuit current, on the other hand, poses considerable challenges to power system protection. In a network with high CIGs penetration, unlike conventional grids, no sub-transient period occurs during a short-circuit event, hence requiring the modification of the protection and control devices. Finally, the non-linear effects induced by the discrete switching operation or saturation of the power converters should be carefully analyzed, since they can trigger cascading events of the protective systems, which require specific functions, e.g., low and high voltage ride-through (LVRT-HVRT) [16].

4. Enabling Technologies for Power System Stability Enhancement

4.1. Rotor Angle Stability

High CIGs penetration sensibly affects the active and reactive power flows, hence influencing the electromechanical vibration characteristics. To assess whether this influence is positive or negative, factors such as penetration level, type, location, force, operation, and the control strategy/parameters (PTLSOC) [4] should be analyzed. As far as transient stability is concerned, both positive and negative effects have been reported in the literature, depending mainly on the size and location of the disturbance and the type of the implemented control [17,18]. In general, there are many case studies reporting positive effects of CIGs on transient stability due to greater flexibility in active and reactive power control [19].

Additionally, the presence of HVDC converters strongly affects power system stability. In this context, [20] proposes the installation of an additional POD (Power Oscillations Damping) controller since the introduction of HVDC lines into the system induced inter-area oscillation modes around 1 Hz, which are different from the typical modes of traditional transmission lines around 0.2 Hz. Therefore, to mitigate these higher frequency oscillations, it is necessary to improve the design of POD controllers so as to avoid unwanted interactions with modes of a different nature that are close to those of the inter-area target modes. Reference [21] evaluates the impact of control structure parameters on the system's intrinsic mode damping and frequency. Indeed, the control system of HVDC converters can be likened to a first-order dynamic system and can be described through two parameters: the control system gain (k_{DC}) and the system time constant (T_{DC}). The study sought to identify parameter pairs that constitute a compromise between network stability and reactivity. Reference [22] proposes a control strategy that is based on a combined approach, which identifies the desired value of the synchronization power by a model-based approach. This control strategy allows improving both the inertial and the frequency response, as demonstrated by detailed simulation studies developed by considering realistic operation scenarios.

Since unstable oscillations can even lead to a system collapse, real-time power system monitoring represents an effective tool for reliably assessing the system stability. To this aim, the spread of phasor measurement units (PMUs) in power transmission systems enables the development of advanced monitoring functions for early detection of dynamic perturbations. In this context, an interesting application is based on the deployment of modal analysis for damping estimation, which is currently used by a Finnish power system operator [23]. Additionally, ref. [24] analyzes real-time monitoring using PMUs, but proposes a decentralized architecture to estimate modal properties highlighting the advantages of such an approach, especially in the detection of local oscillations. PMUs can also be used to detect dangerous oscillations in advance and take appropriate measures. In this regard, in [25], through an optimization of the Hilbert solution method, the measurements provided by PMUs are processed in order to estimate and classify the oscillation components, and the characteristic parameters such as frequency and damping. The proposed method estimated the frequency and damping values with a very good accuracy and also had the advantage of being able to classify oscillations characterized by very close frequency values, so that distinct peaks in the signal spectrum could not be displayed.

The recent wide area measurement system (WAMS) technology can also be used to monitor inter-area oscillations. Reference [26] highlights the advantages of using WAMS technology over conventional power system stabilizers (PSSs). In particular, it analyzes a novel wide-area control technique aimed at modulating the active power injections in the task of damping the critical frequency oscillations, which include the inter-area oscillations and the transient frequency swing. The advantage of using WAMS technology is that multiple remote signals can be used for designing effective control strategies, whereas the PSSs process only local signals. This results in greater robustness of the control actions, since even if the centralized controller link fails, the local controllers continue to operate. Reference [27] evaluates the benefits deriving by the installation of a wide-area power oscillation damper for simultaneously damping both forced oscillations and inter-area modes. The proposed technique is based on an event-triggered strategy, which activates the adaptive control scheme, modulating the voltage set-points of the power oscillation damper. Time synchronized measurements can also enable the development of wide-area damping controllers (WADC), which can be used to damp inter-area oscillations, enhancing the grid observability and controllability [28].

An effective method for analyzing the grid resilience and assessing the correct operation of the main grid components is based on restoration tests, which are based on measurement campaigns aimed at analyzing low-frequency oscillations (LFO) in active power, reactive power and voltage magnitude profiles. Among the possible causes of this phenomenon, Reference [29] focuses on the mutual coupling between the restoration path and the transmission grid in normal operation, identifying, through electromechanical simulations, the main parameters influencing the amplitude and phase of LFOs.

Reference [30] proposes a tool to detect synchronization torque deficiency as a method of prevention against aperiodic rotor angle instability due to small disturbances (ASD). In a first step, the potential buses that can influence the stability margin of the ASD generator are identified by using a Thevenin impedance analysis with respect to a change in nodal admittance; subsequently, the buses are reduced by implementing a sensitivity analysis based on self-propagating graphs, and, finally, the optimal mitigation measures are identified.

4.2. Frequency Stability

The replacement of large synchronous generators with CIGs leads to a dramatic reduction of power system inertia, which could sensibly threaten the frequency stability, especially when the penetration of wind and photovoltaic systems exceed some critical levels [9]. Low system inertia causes a higher rate of change of frequency (ROCOF), and lower/higher nadir/zenith frequency, hence requesting more complex and faster protection systems. In this context, many technical solutions are currently under investigation, such as ultrafast control, virtual inertia, and grid-forming converter control [14]. These techniques aim at allowing generators to support the grid in the presence of transient perturbations by improving the frequency stability [31]. Other approaches propose intentional islanding as a preventive measure aimed at improving the system resilience [32], which has been shown to be an effective method for preventing cascading phenomena induced by HILP (High Impact Low Probability) events, facilitating the identification of pre-contingency mitigation actions.

Dynamic Security Assessment (DSA) is another relevant tool that has been attracted a great amount of attention from both researchers and industry in recent years, mainly due to its effectiveness in accurately describing the grid dynamics in the presence of both external and internal perturbations. However, its application requires the analysis of a large number of operational and failure events, making its online deployment extremely challenging. Hence, DSA is traditionally performed offline, by deploying Monte Carlo simulations for analyzing the dynamic grid evolution in the presence of "credible" contingencies, and estimating the corresponding stability limits. The study [33] draws attention to the possibility of using DSA as an "online" decision support tool by deploying high performance computing (HPC) paradigms in the task of promptly solving multiple contingency analyses under different operation scenarios, according to the strictly time-constraints requested by real-time power system operation functions [34,35]. The adoption of HPC-based DSA has been reported in many case studies: (i) the PJM control centre analyses a 13,500-bus system and can process up to 3000 contingencies every 15 min, (ii) EPRI simulates 1000 contingencies of a 20,000-bus system in about 27 min, (iii) iTesla, which combines offline and online simulations for reducing the total amount of scenarios to be analyzed [36].

To improve power system transient stability, it is possible to adjust in real-time the control strategies of CIGs, by dynamically modulating the generated active and reactive power profiles. In particular, the study [37] analyses the factors mainly influencing power system transient stability, and suggests performing a sensitivity analysis based on a multivariate optimization procedure in order to identify a proper mapping between the active and reactive power profiles that should be generated during a grid contingency.

The frequency stability is strongly related to the inertia of the power system. Reference [38] presents a method for "online" inertia estimation, using the obtained estimation for assessing the grid vulnerability to dynamic perturbations. The proposed estimation method, which is based on the integration of the Wold's decomposition method and then Goertzel's algorithm, uses a second-order infinite impulse response filter to describe the grid dynamics, assuming logistic distributions, and deploying first-order autoregressive models. The proposed method exhibited good performances in a realistic operation scenario, by reliably identifying the actual system inertia, and also detecting critical operation states in the presence of sensible penetration of renewable power generators. Another interesting approach aimed at managing low inertia power systems is proposed in [39], which analyzes the role of synchronous compensators (SC) in the task of increasing the short-circuit power, enhancing the voltage magnitude dynamic after severe grid contingencies. Detailed experimental results obtained on real case studies are also presented in this paper, demonstrating the effectiveness of SCs in enhancing the dynamic performance of low-inertia transmission systems.

Active Power Gradient (APG) control represents another promising technique for enhancing the frequency stability, as demonstrated in [40], which proposed two interesting mathematical methods for adjusting the parameters of APG controllers in order to reduce the frequency deviations after severe power imbalances. Both methods are formulated by a constrained single-objective optimization problem, but the first method aimed at minimizing the instantaneous variation of the kinetic energy of the synchronous areas, while the second one aimed at minimizing the spatial shifts between the dynamic trajectories of the temporal responses in different synchronous areas.

4.3. Voltage Stability

The massive penetration of CIGs into the transmission and distribution grid makes the voltage regulation process much more complex. In this context, short-term voltage stability could be compromised due to the fast dynamic response of the converters, which could induce severe transient voltage disturbances (e.g., over/undervoltages) [41].

Among the possible mitigation techniques that could be deployed for enhancing the voltage stability, those based on synchrophasors-based data processing are the most promising. These techniques allow detecting voltage instability and implementing load reduction techniques by processing time-synchronized measurements acquired by a network of PMUs. However, the application of these techniques is still embryonic, and several open problems should be fixed in order to obtain a complete and reliable system observability. In this context, the uncertainties induced by measurement errors, the accuracy and integrity of the time-synchronization sources, and the vulnerability of PMUs to cyberattacks are some of the relevant issue to address [42,43].

A useful analysis of the main effects induced by DFIG-based wind generators on voltage stability is presented in [44], which identifies the effects of these generators on maximum loadability limits and the maximum scalable active power demand, clearly emphasizing that an increasing penetration of wind power generators can overload critical grid equipment, hence limiting their hosting capacity. Similarly, in [45], the impact on the long-term voltage stability (LTVS) of photovoltaic generation is assessed. In particular, this study showed that solar generation can also have both negative and beneficial effects on voltage stability. Furthermore, the parameters that most affect LTVS were identified, including solar irradiation and ambient temperature, inverter power, reactive power gain and current-limiting strategies.

A further cause of voltage instability is the decommissioning of conventional synchronous generators, which lowers the available reactive power reserve. In this context, Reference [46] performs a comprehensive voltage stability analysis computing the VQ stability margins, emphasizing the fundamental role played by the reactive power control strategy and reactive power capacity of converter-interfaced technologies in ensuring voltage stability. According to this important result, several studies suggest the deployment of additional devices aimed at enhancing voltage stability by improving reactive power reserves, such as synchronous capacitors, synchronous static compensators (STATCOM), switchable and non-switchable shunt capacitors and reactors, and on-load tap changing transformers (OLTCs) [47].

4.4. Converter-Driven Stability

Many experimental studies developed worldwide demonstrated converter-driven stability issues that could induce unstable power system operations due to a number of complex dynamic phenomena, which include sub-synchronous oscillations between wind generators and series compensated lines [48], and harmonic instability induced by solar generators [49]. These phenomena can be generated by a combination of multiple effects, such as interactions between the CIGs control units, power system weakness, converter-interfaced load dynamics, and congested power lines [50]. In particular, the fast dynamic of the CIGs power/voltage control unit could induce rapid variations of the grid frequency and transient distortions of the voltage waveform, which could trigger the grid protections [51]. In this context, it is extremely important to accurately analyze and classify all the potential sources of converter-driven instabilities, in order to design and implement robust corrective actions aimed at mitigating the dynamic perturbation effects of these phenomena on correct power system operation.

4.5. Resonance Stability

Resonance stability issues are mainly related to the torsional impacts of flexible alternating current transmission systems and/or high-voltage direct current transmission systems, and the electrical resonances originating from the grid interactions of the CIGs controllers. The analysis of these oscillatory phenomena can be performed according to different computing techniques, which include time-domain electromagnetic power system simulation, state-space analysis, and frequency-domain impedance-based methods. In particular, electromagnetic power system simulation requires the numerical solution of the differential equations describing the dynamics of the power electronic components of the CIGs. Although these techniques allow accurately modeling the grid oscillations, they could not allow analyzing the intrinsic phenomena ruling the oscillations [52]. State-space analysis-based methods allow overcoming this limitation, by analyzing the eigenvalues of the state-matrix in the task of detecting unstable oscillation modes, determining the main parameters influencing their evolution [53]. Despite these benefits, developing a state-space model for power systems in the presence of a large number of CIGs is a challenging issue. In this context, the complexities in describing the reactive effects of the power transmission system, and the dynamic of the power electronic converters are some of the most relevant issues to address. The deployment of frequency-domain impedance-based methods represent a promising alternative approach for resonance stability analysis. The mathematical backbone supporting these approaches is based on the Nyquist stability criterion of the single port-impedance, which can be easily developed by using different modeling approaches, such as small-disturbance models, harmonic linearization, and the measurement methods [53]. Recently, more effective modeling approaches based on the s-domain nodal admittance matrix analysis have been proposed in the task of accurately analyzing the resonance stability of power systems in the presence of a large-scale penetration of CIGs [54]. The application of these modeling approaches allows identifying the main phenomena affecting resonance stability, and analyzing the potential technical solutions aimed at enhancing the grid robustness against these phenomena. In this context, the most promising mitigation techniques include the deployment of static var compensators for damping the torsional resonance, and the smart coordination of the CIGs controllers in the task of damping the electrical resonance [50].

5. Open Problems and Future Research Directions

The large scale integration of CIGs in power transmission and distribution networks, and the consequent decommitment of conventional synchronous generators, is reducing the system inertia inducing new and complex stability issues. In particular, an increasing number of both conventional perturbation phenomena (i.e., characterized by a time-frame of seconds), and new fast stability phenomena (i.e., characterized by shorter time scales, ranging from micro to milliseconds) have been observed in recent years. These phenomena could significantly affect power system stability, generating major challenges to system operators, which should revise their network codes in order to ensure that the power electronic interfaces of both generators and loads should provide proper grid stabilizing capabilities [55], defining new resilience requirements aimed at enhancing system stability in daily operation and during severe grid perturbations. To this aim, it is also important to define reliable markets schemes and effective regulations in order to stimulate the availability of grid flexibility sources at reasonable costs. Moreover, it is extremely important to support the large scale deployment of the enabling technologies for grid stability enhancement, in order to properly mitigate the impacts of the increasing number of CIGs. Finally, in the authors' opinion, the most promising research directions include the development of:

- Measurement-based methods for the online estimation of the power system inertia, and for assessing its (minimum) critical value.
- Condition monitoring systems aimed at predicting and monitoring the power system stability.
- Decision support systems for online control of the grid flexibility sources and the distributed energy resources in the task of enhancing the system stability, security and resiliency.
- Harmonization and interoperability standards defining the technical capabilities, the connection specifications, and the grid support services (e.g., grid forming, fast frequency reserves) of inverter-based resources.
- Advanced modeling platforms for real-time simulation of CIGs-dominated power systems.
- Market schemes aimed at ensuring the availability of grid flexibility resources aimed at maintaining the power system stability, security and resiliency.

6. Conclusions

This paper analyzed the classification of power system stability according to the recent revisions proposed in the literature in the task of characterizing the dynamic perturbation phenomena induced by a large penetration of converter-interfaced generators in transmission and distribution grids. Starting from this analysis, the potential grid impacts deriving by the replacement of conventional synchronous generators with distributed renewable power generators are presented and discussed, outlining the new challenging issues, the most promising research directions and the main mitigation technologies. The presented analyses demonstrated that the conventional strategies currently adopted in power system operation and planning should be revised in order to enhance the grid robustness to dynamic perturbations, which could induce severe consequences, especially in low-inertia systems. In this context, it is expected that the grid control and protection techniques will undergo profound changes to adapt to a new way of managing the grid, as will operation and planning criteria. In this scenario, it is pivotal to conduct new studies on the stability of the system and to investigate the effects that dynamics over several time scales and any undesirable coupling have on the grid.

Author Contributions: Conceptualization, A.V. and C.P.; investigation, G.M.G., C.P., S.T. and A.V.; writing—original draft preparation, V.M. and A.V.; writing—review and editing, V.M., S.T.; supervision, G.M.G., C.P. and A.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

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

Abbreviations

The following abbreviations are used in this manuscript:

APG	Active Power Gradient
ASD	Aperiodic Small Disturbance
CIG	Converter Interfaced Generation
DFIG	Doubly-Fed Induction Generator
DSA	Dynamic Security Assessment
FACTS	Flexible Alternating Current Transmission System
HIL	Hardware In Loop
HILP	High Impact Low Prequency
HPC	High Performance Computing
HVDC	High Voltage Transmission System

HVRT	High Voltage Ride-Through
LFO	Low Frequency Oscillation
LTVS	Long-Term Voltage Stability
LQR	Linear Quadratic Regulator
LVRT	Low Voltage Ride-Through
OLTC	On-Load Tap Changing
PMU	Phasor Measurement Unit
POD	Power Oscillations Damping
PSS	Power System Stabiliser
ROCOF	Rate Of Change Of Frequency
SC	Synchronous Compensator
SCADA	Supervisory Control And Data Acquisition
SG	Synchronous Generators
STATCOM	Static Synchronous Compensator
SVC	Static VAr Compensator
TSO	Transmissin System Operator
WADC	Wide Area Damping Controller
WAMS	Wide Area Measurement System
WAPOD	Wide Area Power Oscillation Damper

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