Impedance Methods for Analyzing the Stability Impacts of Inverter-Based Resources: Stability Analysis Tools for Modern Power Systems

Article *in* IEEE Electrification Magazine · March 2021

DOI: 10.1109/MELE.2020.3047166

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Impedance Methods for Analyzing the Stability Impacts of Inverter-Based Resources

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Stability analysis tools for modern power systems.

POWER SYSTEMS AROUND THE WORLD are undergoing a major transformation because of the increasing shares of renewable energy, growing deployment of energy storage systems, proliferation of distributed energy resources, electrification of other sectors, and so on. In the United States, wind and solar provided almost 10% of electricity in 2019. The U.S. Energy Information Administration, in its 2020 Annual Energy Outlook, forecasted that the share of electricity from renewables will reach 38% by 2050, of which more than 80% will come from wind and solar. Wind and solar, along with battery

Digital Object Identifier 10.1109/MELE.2020.3047166
Date of current version: 4 March 2021

energy storage systems, interface with the grid using power electronic inverters; hence, they are collectively referred to as *inverter-based resources* (IBRs). The increasing annual share of electricity from IBRs in a power system means that during more times of the year, the system will operate at a much higher concentration of IBRs. Figure 1 presents the hourly share of wind and solar generation in the Electric Reliability Council of Texas (ERCOT) system in Texas in 2019. While the annual wind share was at 20%, the instantaneous percentage share was much higher. Moments of high shares of IBRs (>50%) will continue to grow as more IBRs will be deployed in a power system.

Dynamic stability is a major concern in maintaining the security of power grids as the generation mix transitions to include high shares of IBRs.

Small island power systems are generally the first to experience very high levels of IBRs, but several mainland power system networks—such as Texas, South Australia, Denmark, and Ireland—also routinely operate with high instantaneous levels of IBRs. The number of power grids experiencing high instantaneous levels of IBRs, at least in some of their regional areas, will only increase with the rising integration of low-cost wind and photovoltaic (PV) energy resources. Dynamic stability is a major concern in maintaining the security of power grids as the generation mix transitions to include high shares of IBRs. Small-signal stability problems in power systems before the advent of IBRs constituted only low-frequency local and wide-area oscillations due to the interaction between the electromechanical dynamics of synchronous generators; however, the integration of large amounts of IBRs has caused new types of stability problems in power grids that manifest at frequencies ranging from a couple of hertz to tens of kilohertz because of the fast and complex controls of IBRs. The increased levels of IBRs also threaten the fundamental frequency and voltage stability of the grid because of the lack of inertia and current-sourcing capability of IBRs.

System Strength and Stability

As displayed in Figure 2, the IBR-related stability problems can be classified as subsynchronous resonance, near-synchronous resonance, or supersynchronous resonance, depending on the frequency of the oscillations in three-phase voltages and currents. Near-synchronous resonance problems result from the interactions among the slower control loops of IBRs used for regulating phasor quantities, such as active and reactive power output and the magnitude and frequency of voltages at the point of interconnection. Supersynchronous or harmonic resonance issues result from the interactions of the faster control loops of IBRs, including current control and grid synchronization using a phase-locked loop (PLL). The operation of IBRs in regions with low system strength and higher grid impedances has been found to be the main reason behind many of the harmonic resonance problems. Weak grid conditions also compound near-synchronous resonance problems, particularly when many IBRs operate in proximity to and connect to weak power grids. Note that near-synchronous resonance in three-phase voltages and currents manifests as low-frequency or subsynchronous oscillations (SSO) in phasor or dq quantities, such as active and reactive power flows and the magnitude and frequency of bus voltages; hence, near-synchronous resonance is also referred to as SSO. However, it is important to differentiate SSO in phasor quantities from SSO in three-phase voltages and currents because the fundamental mechanisms behind these problems are significantly different.

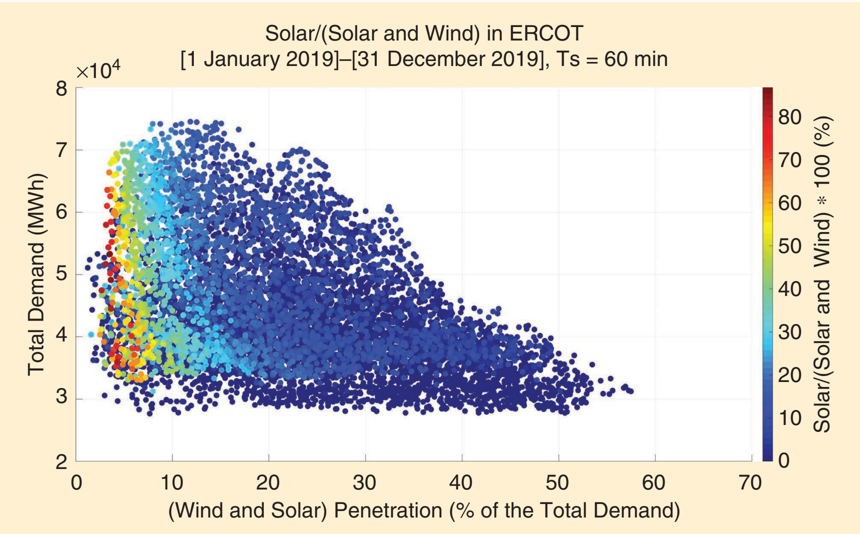

Figure 1. The hourly percentage share of wind and solar generation in ERCOT in 2019. (Source: Generated by Ning Zhou, Binghamton University and Renke Huang, PNNL for WETO). PNNL: Pacific Northwest National Laboratory; WETO: Wind Energy Technologies Office.

Figure 3 represents the system strength in different parts of the power system that serves the eastern and southern Australian states. As illustrated, the system strength in certain regions with high levels of IBRs will be low, which increases the risks of IBR-related stability problems. The impacts of IBRs on system stability must be properly evaluated to maintain the reliability of power systems and to plan future investments in the transmission system.

Stability Analysis Tools

Commercial eigenvalue analysis tools along with positive-sequence phasor-domain simulations are commonly used for evaluating the stability of bulk power systems. These tools depend on open-box (i.e., publicly available) models of synchronous generators and the transmission network; however, they cannot be applied to evaluate the impact of IBRs on system stability because of the following reasons:

1) IBRs use diverse and nonstandardized control methods, and they cannot be represented using generic and simple models as is possible with synchronous generators
2) IBRs must be represented using detailed electromagnetic transient (EMT) models because their complex dynamics cannot be captured in positive-sequence phasor models
3) manufacturers only supply the black-box EMT models of IBRs that do not disclose internal details on the control system architecture and parameters
4) IBRs have complex dynamic behavior because of the large number of nonlinearities, such as PLL, limiters, and different control modes, which limits the applicability of eigenvalue analysis for understanding the stability problems associated with IBRs.

These limitations of the model-based tools can be addressed by data-driven stability-analysis approaches. Impedance-based stability analysis is one such data-driven tool that has proven effective in evaluating stability problems involving IBRs. It can use the frequency-domain impedance responses of IBRs—obtained using either actual measurements or from black-box EMT models—for analyzing the stability impacts of IBRs without requiring internal details on power hardware, control architecture, and parameters. The objectives of this article are to present historical and modern developments in impedance methods, show their applications for stability analysis of wind and PV power plants as well as high-voltage direct current (HVdc) transmission networks, and provide recent developments that make impedance methods suitable for grid-level studies used for analyzing the stability of future grids with high levels of IBRs.

Impedance Method for Stability Analysis

The impedance-based stability-analysis method was originally introduced in 1976 by Prof. R. D. Middlebrook to evaluate the dynamic interactions between a converter-based dc power supply and its source with an electromagnetic interference filter. Figure 4 demonstrates the method for the stability analysis of a grid-connected IBR: The interconnection of an IBR with a grid forms a negative feedback loop whose loop gain is given by the impedance ratio, $Z_g(s)/Z_i(s)$, where $Z_g(s)$ is the grid impedance as seen from the IBR terminals, and $Z_i(s)$ is the internal impedance of the IBR. The stability of the interface between the IBR and the grid can be analyzed by applying linear system-analysis tools to the loop gain, $Z_g(s)/Z_i(s)$. Either the Nyquist stability criterion is applied to the loop gain, $Z_g(s)/Z_i(s)$, or the

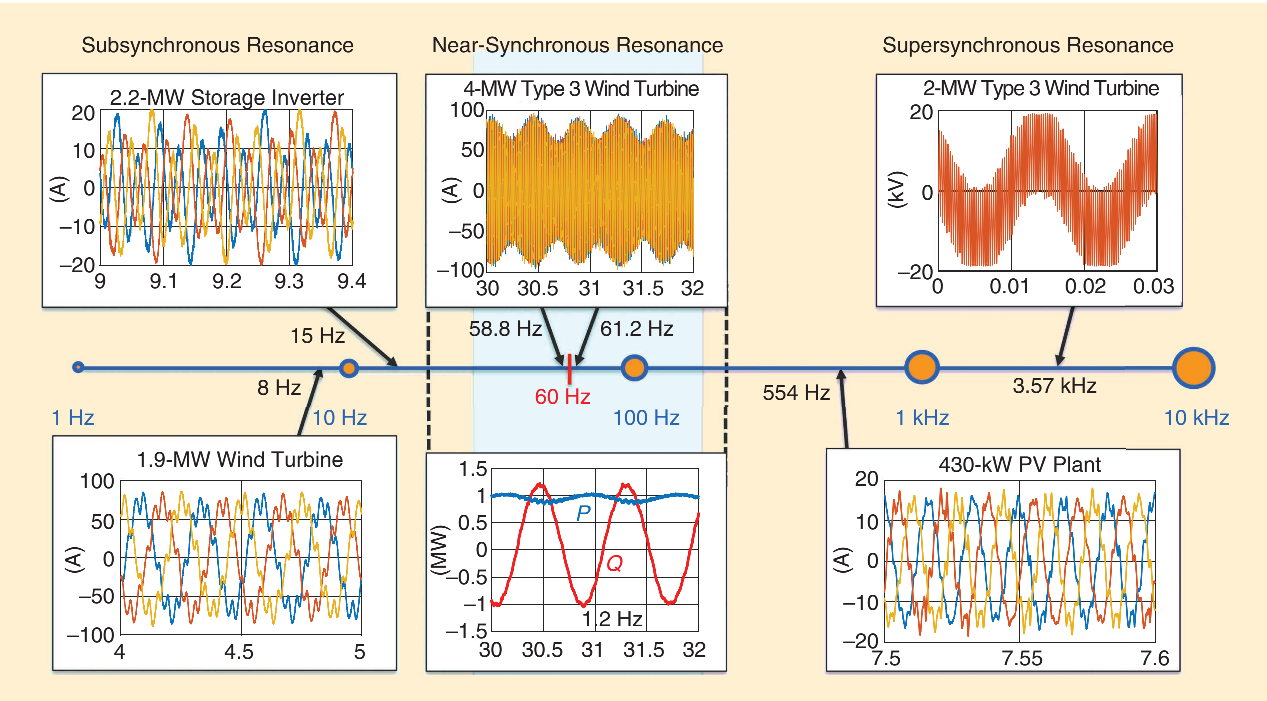

Figure 2. The stability problems in power systems with high levels of IBRs. All waveforms in this figure are real measurements.

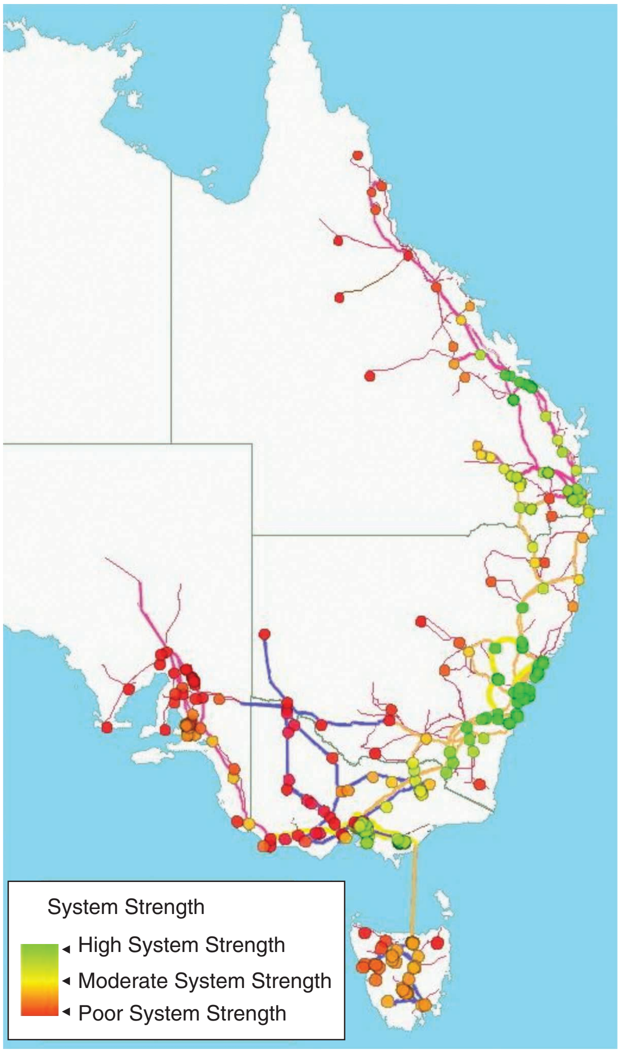

Figure 3. The system strength outlook of NEM network in Australia for 2020–2021. NEM: National Electricity Market; AEMO: Australian Energy Market Operator; ISP: Integrated System Plan. (Source: AEMO 2020 ISP Report Appendix 7: Future Power System Security, July 2020; Used with permission.).

Bode plots of the two impedance transfer functions, $Z_g(s)$ and $Z_i(s)$, are compared for the stability analysis.

dq Impedance Approach

In 1997, M. Belkhayat extended the impedance method to three-phase ac systems by using impedance defined in a synchronously rotating, dq reference frame. Because the dq impedance of a three-phase network is a two-by-two transfer matrix instead of a scalar transfer function, the Nyquist criterion for single-input, single-output (SISO) systems or Bode plots cannot be used for the stability analysis of three-phase ac systems using the dq impedance approach. Instead, the generalized Nyquist criterion for multiple-input, multiple-output systems are required for the stability analysis. This does take away some intuition from the frequency-domain, impedance-based analysis, but the method offers several advantages compared to time-domain, state-space modeling and analysis because it supports the use of impedance measurements and black-box EMT models for the stability evaluation.

Sequence-Impedance Approach

Different from the dq-impedance approach, in 2009, J. Sun proposed the use of positive- and negative-sequence impedances to perform the stability analysis of three-phase ac systems. It was understood that the positive- and negative-sequence impedances of IBRs, under balanced operation conditions, are uncoupled and that they can be represented by two scalar transfer functions, which enables the use of the SISO Nyquist criterion and Bode plots for the stability analysis. However, recent works have shown that IBRs exhibit so-called frequency-coupling effects, as displayed in Figure 5, which introduce coupling between the positive- and negative-sequence impedances at low frequencies below the second harmonic of the fundamental frequency. This limits the applicability of the SISO Nyquist

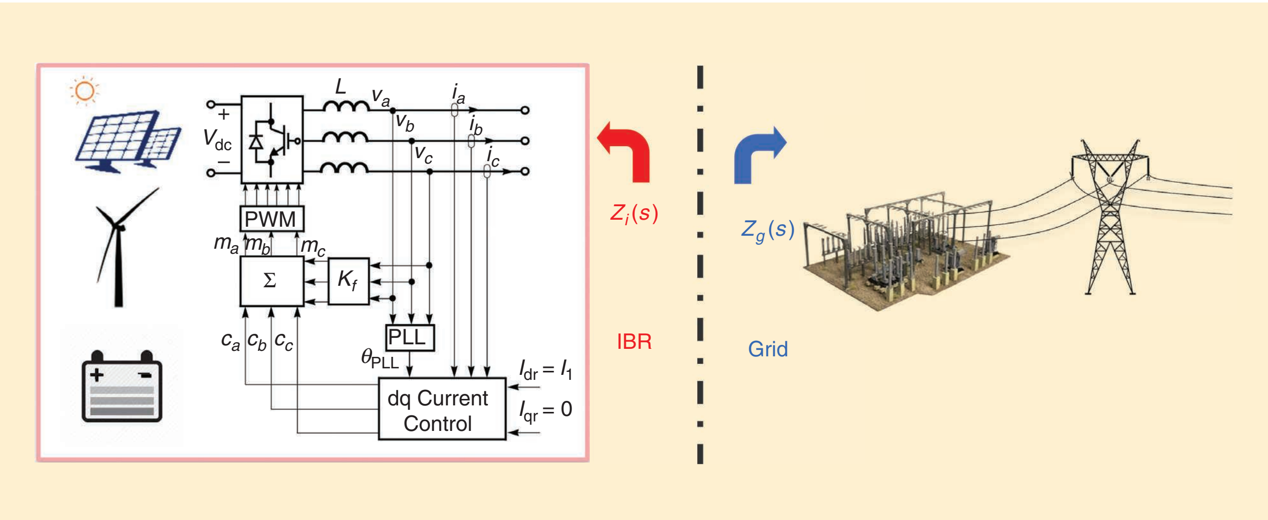

Figure 4. The impedance method for stability analysis. PWM: pulsewidth modulation.

criterion and Bode plots using the sequence-impedance approach. Nonetheless, the sequence-impedance approach offers several advantages: 1) It does not require Park's transformation of voltage and current measurements, and it performs the stability analysis in a stationary reference frame whose results are easier to interpret for control design and for developing mitigation solutions for stability problems; 2) sequence impedances are uncoupled at high frequencies, which permits the analysis of supersynchronous resonance problems using the more-intuitive SISO Nyquist criterion or Bode plot analysis methods; and 3) the sequence impedance of IBRs at low frequencies can still be represented by uncoupled positive- and negative-sequence impedances for stability analysis in the presence of the frequency-coupling effects as long as the grid does not exhibit frequency-coupling effects. The uncoupled positive- and negative-sequence impedances, including the frequency-coupling effects, considerably simplify the analysis of subsynchronous and near-synchronous stability problems, but they are dependent on the grid impedance.

Both forms of the impedance method using the dq and sequence impedances are used by the power electronics community. However, because of the advantages it offers, the sequence-impedance approach is increasingly preferred for the stability analysis of renewable energy and HVdc transmission systems.

Phasor Impedance Approach

It is not practical to partition a network in the source-load configuration, as shown in Figure 4, for applying the impedance method for grid-level stability studies with numerous IBRs connected at different points in the grid. The impedance responses of IBRs must be integrated with the ybus or zbus matrix of the bulk power system. However, phasor models are generally used to represent the bulk system, including synchronous generators and the transmission network. These models use magnitudes and angles of three-phase voltages and currents as state variables instead of representing them by instantaneous quantities. To integrate the impedance models of IBRs with the phasor models of the bulk system, a phasor-impedance approach was introduced by S. Shah in 2017. The phasor impedance of a three-phase network is the two-by-two transfer matrix from the magnitude and angle of three-phase currents to the magnitude and angle of three-phase voltages at the terminals of the network. The phasor-impedance approach imparts scalability to the impedance method to use it for grid-level stability studies. It has been shown that the dq, sequence, and phasor impedances are mathematically equivalent, and the choice between the three is primarily governed by the ease with which the impedance-based stability analysis can be performed and the results can be interpreted.

Applications

Since the early 2000s, when the impedance method was extended to three-phase ac systems, it has been used for the stability analysis of different ac power systems, such as shipboard power systems, more-electric aircrafts, microgrids, and electric traction networks. However, during the last 10 years, the growth of wind and PV generation and the use of HVdc transmission for integrating large amounts of renewable generation have tremendously increased the number of applications where the impedance method is applied for stability analysis. Next, we describe some use cases of the method.

Since the early 2000s, when the impedance method was extended to three-phase ac systems, it has been used for the stability analysis of different ac power systems.

Wind Power Plants

Several SSO events involving wind power plants were recorded in the Xcel system in Minnesota after, in 2007, series compensation capacitors were installed in a 345-kV transmission line to accommodate rapidly increasing wind generation in the region. These events resulted not only in the tripping of wind and conventional generation units but also caused damage to wind turbines and substation equipment. All of these events involved wind power plants with doubly-fed induction generator-based Type 3 wind turbines. Type 3 wind turbines are prone to SSO problems when they supply radially to a series-compensated transmission line. Similar SSO events have become more common in the ERCOT system in Texas since the first event in 2009 because of the large concentration of wind generation in the Texas Panhandle region and the use of several series-compensated transmission lines to export renewable energy from the Panhandle to the major load centers in Texas. ERCOT has mandated performing impedance-based frequency-scan studies before commissioning new wind power plants if the plant demonstrates the risk of getting

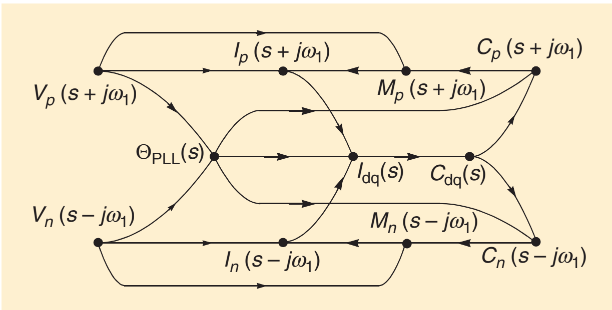

Figure 5. The frequency coupling effects between positive and negative sequence dynamics in IBRs.

connected radially to a series-compensated transmission line during a contingency event. The objective of such studies is to estimate the incoming wind power plant's vulnerability to SSO and to advise vendors to incorporate damping controls in the wind turbines if necessary. SSO events have also occurred in Northern and Western China, which have large concentrations of wind generation. Not all of these events involved Type 3 wind turbines or series-compensated transmission lines; some occurred because of wind power plants, using Type 3 or 4 wind turbines, interacting with the weak electrical network and HVdc transmission lines. Impedance methods are extensively used by the State Grid Corporation of China for evaluating these complex stability issues involving wind power plants from different vendors with both Type 3 and 4 wind turbines, conventional generation units, and long ac and dc transmission lines. Controller-hardware-in-the-loop (CHIL) real-time simulations are used with actual industrial controllers of wind turbines for performing impedance studies to identify and mitigate potential SSO problems.

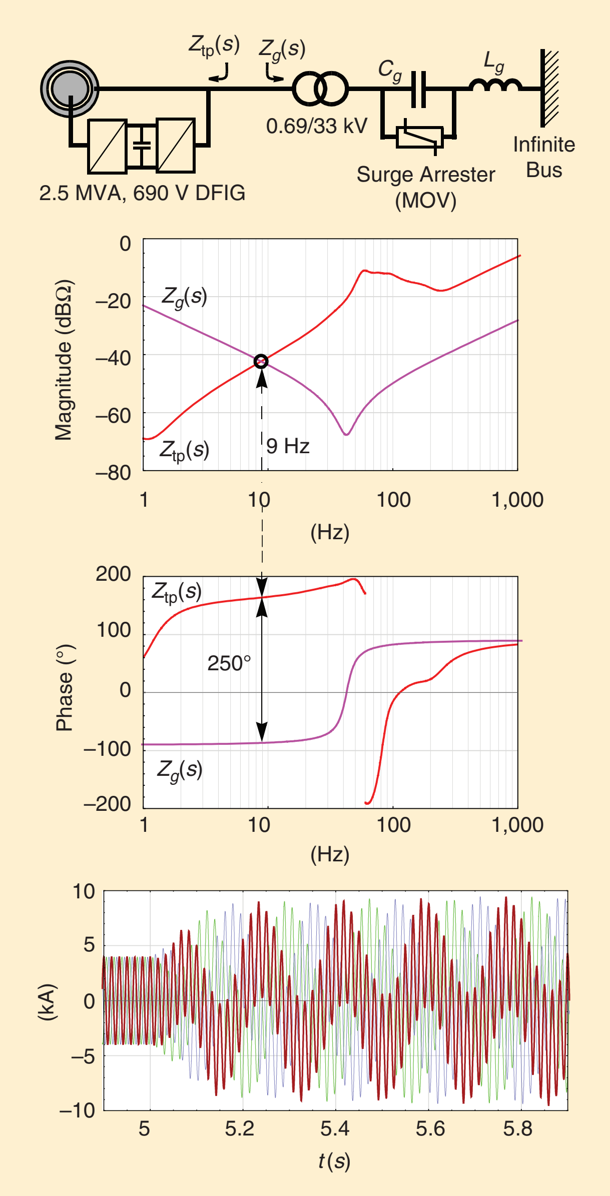

Figure 6. An impedance-based analysis of SSO in Type 3 wind turbines. MVA: mega-volt-ampere; MOV: metal-oxide varistors.

Figure 6 demonstrates an example impedance analysis of the interaction between a Type 3 wind turbine and a series-compensated transmission line by comparing their positive-sequence impedance responses. The inductive-impedance response of the turbine intersects with the capacitive-impedance response of the compensated line at 9 Hz. The impedance response of the wind turbine exhibits negative damping in the subsynchronous frequency range because of the induction-generator effect and active control of the rotor-side converter. Because of this negative damping, the interaction between the turbine and the line at 9 Hz has a negative phase margin of –70° (= 180°–the phase difference between the two impedances at the intersection frequency), indicating instability. EMT simulations in Figure 6 confirm that the insertion of series capacitors results in SSO in the wind turbine output currents.

Large-Signal Impedance Analysis

One major limitation of small-signal stability analysis—using either the impedance or eigenvalue analysis method—is that it can predict only an approximate frequency of oscillations when a system becomes unstable, and, more importantly, it cannot predict the magnitude of oscillations that an IBR might experience during instability. As an example, although the impedance analysis presented in Figure 6 predicted instability at 9 Hz, the EMT simulations showed SSO at 5.5 Hz of 1 p.u. magnitude. Most IBRs usually experience sustained oscillations during an instability event (as illustrated in Figure 2); the oscillations continue to persist in the system, sporadically appear and disappear with changing operation conditions, cause equipment damage, or eventually trigger some protection and trip the system. For protection design and to avoid equipment damage, it is very important to estimate the magnitude of the oscillations an IBR might experience under potential unstable operation scenarios.

A large-signal impedance theory was recently developed by Shah in 2017 to accurately estimate the frequency and magnitude of oscillations during instability events involving IBRs. The fundamental principle behind the theory is that as oscillations start growing because of small-signal instability, different nonlinearities in the system dynamics (including control or PWM saturation in power electronics converters; also including limiters to control signals, such as current and power references; magnetic saturation, and protection functions) might change the impedance response of different components and stop the growth of oscillations beyond a certain point. Figure 7 presents the application of the large-signal impedance theory for predicting the magnitude of SSO observed in Figure 6.

As displayed, the impedance of the series-compensated transmission line starts changing with the magnitude of the current perturbation used for the impedance measurement because of the surge-arrestor protection of capacitors. This changes the frequency and phase margin of the interaction between the wind turbine and the series-compensated transmission line. The interaction gets stabilized—that is, the phase margin becomes nonnegative—for the current perturbation of approximately 1 p.u.. Moreover, the interaction frequency for this level of perturbation is 5.5 Hz. Hence, the large-signal impedance analysis in Figure 7 predicts the frequency and magnitude of SSO to be 5.5 Hz and 1 p.u., respectively, which are the same as observed in the EMT simulations in Figure 6.

Offshore Wind Energy Systems

The impedance method has proven particularly successful in the development of offshore wind energy systems because these are multivendor systems involving several wind turbine, transmission, and HVdc equipment vendors. The impedance method supports stability analysis using black-box EMT models from different vendors without disclosing their intellectual property to other vendors or the system integrator. The impedance responses of different equipment can be obtained by performing a frequency sweep on the black-box EMT models to evaluate various types of stability problems.

Figure 8 illustrates a schematic of an offshore wind power plant along with different transmission options to bring the offshore wind energy to the grid. Offshore wind energy systems with hundreds of wind turbines and possibly several HVdc converters have a very high density of power electronics converters within a small geography. The fast and complex controls of these many power electronics devices, in proximity without significant electrical impedance between them, make offshore wind energy systems particularly prone to various types of control interaction and stability problems. Offshore wind energy systems' connection to the land-based grid in the vicinity of coastal load centers, which are already experiencing congestion problems, aggravates the risks of stability problems that they face. A stability event involving an offshore wind power plant occurred in the BorWin1 plant in the North Sea of Germany in 2014. BorWin1 is the first offshore wind power plant to employ HVdc transmission. The stability event happened after the wind plant's output level was raised to its rated capacity. The BorWin1 plant started interacting with the offshore HVdc rectifier substation in an unstable manner, which resulted in a supersynchronous or harmonic-resonance event. The ensuing oscillations damaged the filters of the HVdc converter station, which resulted in the wind power plant remaining out of operation for several months. The loss of revenue from this disruption was calculated to be in the order of hundreds of millions of Euros. Since this highly publicized stability event, many control-interaction and stability problems have happened in the offshore wind energy systems in Europe, with the most recent being the August 2019 event in the Hornsea offshore wind power plant in the United Kingdom. The event involved low-frequency reactive-power oscillations in the wind power plant output, following a remote fault in the transmission grid. The oscillations tripped the wind power plant, and the sudden loss of wind generation resulted in a country-wide blackout.

Because of these stability events, impedance methods are being extensively included in the planning and development of offshore wind energy systems in the North Sea region of Europe. They are applied to study control interactions among wind turbines in a plant, among multiple offshore wind power plants sharing the offshore transmission link, between a wind power plant and the offshore HVdc substation, among land-based and offshore HVdc substations, and between the land-based HVdc substation and the grid. Some transmission system operators, such as TenneT in Germany, mandate that offshore wind power plant developers conduct comprehensive impedance-based stability studies using vendor-supplied black-box EMT models of wind turbines and HVdc equipment. Figure 9 displays one example of the complexity of interactions in offshore wind energy systems. It demonstrates the reflection of an unstable resonance on the ac side of an HVdc converter station in its dc-side input impedance response. As illustrated in Figure 9, the ac-side impedance analysis predicts an unstable resonance at 97 Hz, which is also observed in EMT simulations. This resonance is reflected in the dc-side input impedance of

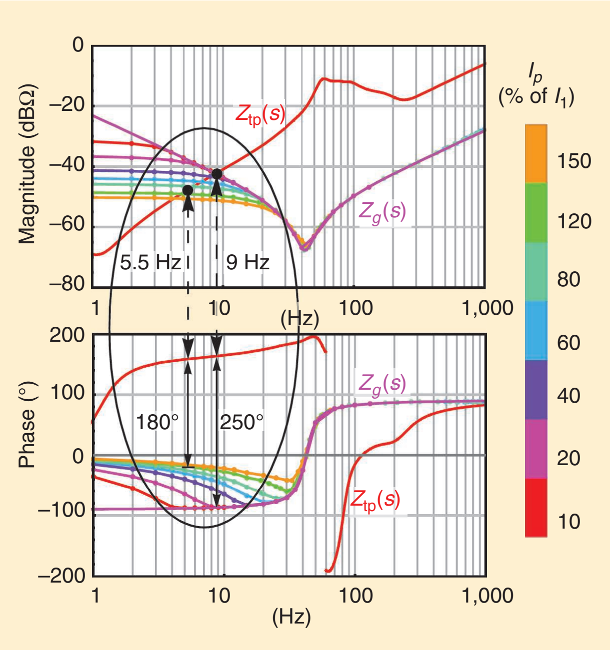

Figure 7. A large-signal impedance analysis for predicting the magnitude of SSO.

the HVdc converter station at 37 Hz because of the complex frequency cross-coupling between the ac- and dc-side dynamics of the HVdc converters.

PV Power Plants

The impedance method has been applied for studying the stability of PV power plants. As an example, Figure 10 presents an impedance-based stability analysis of a 430-kW PV power plant at the National Renewable Energy Laboratory (NREL). It compares the positive-sequence impedance response of the PV plant, which includes six string inverters, with the impedance of the grid at the terminals of the PV plant. The impedance analysis displayed in Figure 10 predicts an unstable harmonic resonance at 554 Hz, with a negative phase margin of –4.5°. The plant experienced harmonic resonance for this particular grid condition; the output currents of the PV plant during the resonance are presented in Figure 2.

Impedance Measurement of IBRs

The impedance responses required for stability analysis can be obtained by performing either real measurements or a frequency sweep on EMT simulation models. Model-based impedance estimation, however, is possible only when high-fidelity black-box, "real-code" EMT models are provided by vendors. Moreover, depending on how the vendor-supplied EMT models are validated, the impedance responses obtained using such models might not be accurate at all frequencies. Hence, impedance measurement is an important grid-integration test to understand the dynamic stability characteristics of IBRs and to validate EMT models over a broad frequency range. Impedance

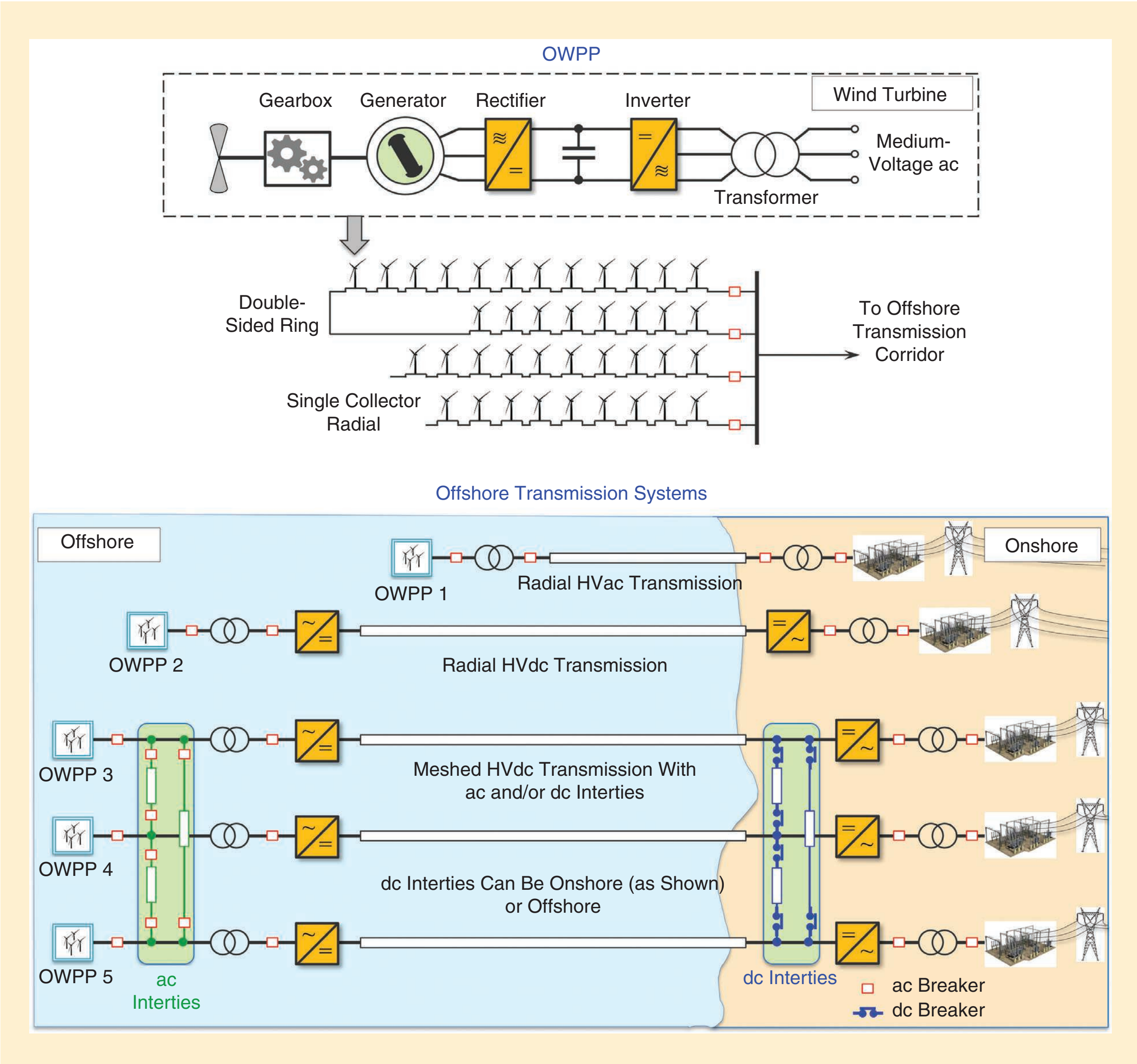

Figure 8. An offshore wind power plant (OWPP) and transmission systems. HVac: high-voltage alternating current.

measurements can also be used for real-time stability monitoring and for the adaptive control of IBRs during changing grid and operation conditions.

Measurement Using Multimegawatt Grid Simulators

Multimegawatt grid simulator facilities are used in several parts of the world to conduct grid integration tests—such as low- and zero-voltage ride-through tests, frequency and phase jump tests, steady-state volt-var characterization, and operation with different grid strengths—on wind turbines and inverters. Grid simulator facilities can also be configured to conduct impedance measurements of IBRs. Grid simulators can be programmed to inject small-signal voltage perturbations at different frequencies superimposed on the fundamental voltages for impedance measurements. Voltage perturbations can be designed in the dq, sequence, and phasor domains to obtain impedance responses in different domains.

Figure 11 displays the 7-MW grid simulator, the controllable grid interface (CGI), at the Flatirons Campus of

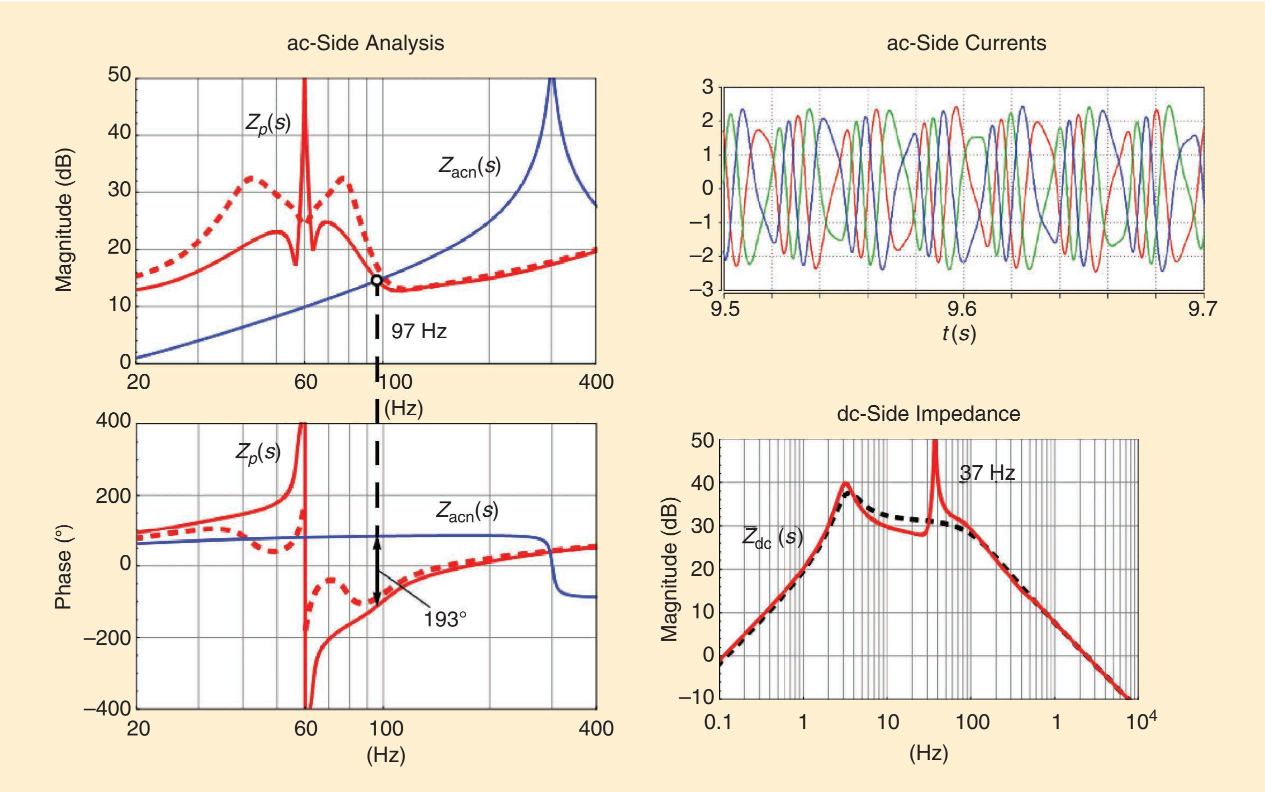

Figure 9. The reflection of resonance at 97 Hz on the ac side of an HVdc converter station in its dc-side input impedance at 37 Hz.

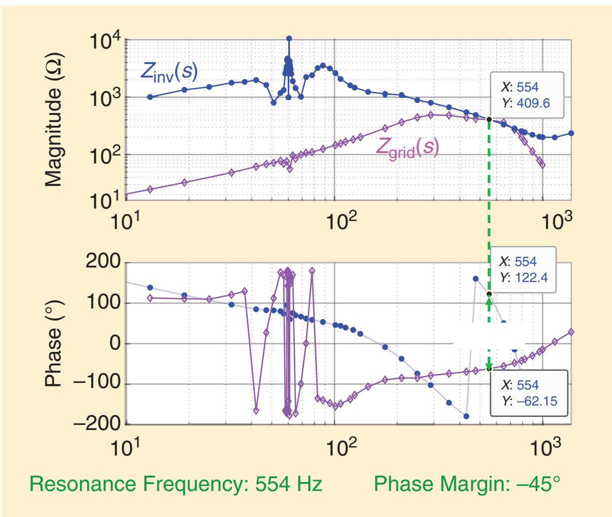

Figure 10. An impedance analysis of interaction between a 430-kW PV plant and the grid.

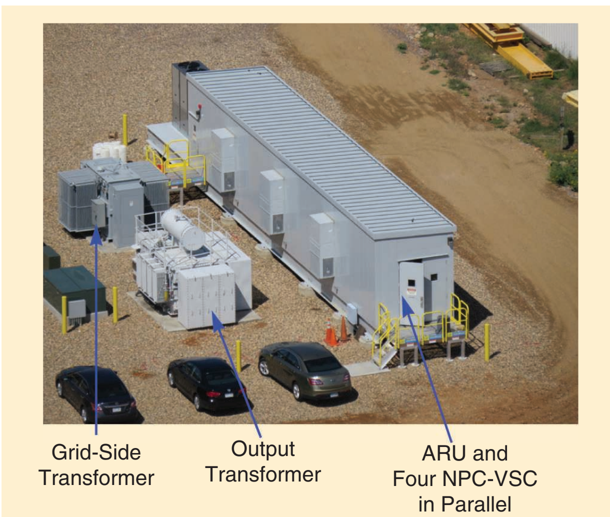

Figure 11. A 7-MW grid simulator. ARU: active rectifier unit; NPC-VSC: neutral-point clamped voltage source converter. (Source: NREL.)

NREL. It was commissioned in 2013–2014, and it is used to conduct a wide variety of grid-integration tests on wind turbines and PV/storage inverters. Figure 12 presents a schematic of the impedance-measurement system developed at NREL around the CGI. As illustrated, medium-voltage data-acquisition system nodes are used to take GPS-synchronized measurements of three-phase voltages and currents during the injection of voltage perturbations at different frequencies. These measurements are postprocessed using fast Fourier transform analysis to obtain Fourier components at the perturbation, coupling, and fundamental frequencies. These Fourier components are then used to obtain the impedance response. The impedance-measurement system at NREL can perform measurements over a wide frequency range—from a fraction of hertz to several kilohertz. Figure 13 displays the sequence-admittance response of a 1.9-MW wind turbine measured at NREL. The figure shows the positive-sequence admittance, $Y_p(s)$, and the coupling admittance, $Y_{cp}(s)$, of the turbine. Note that the coupling admittance is the gain from the injected voltage perturbation to a current response at the coupling frequency, which is given by f_p-$2f_1$, where f_p is the frequency of the injected perturbation, and f_1 is the fundamental frequency. It is evident from Figure 13 that the coupling admittance cannot be ignored below 120 Hz. Hence, as noted previously, the frequency-coupling effects must be considered for the analysis of subsynchronous and near-synchronous stability problems.

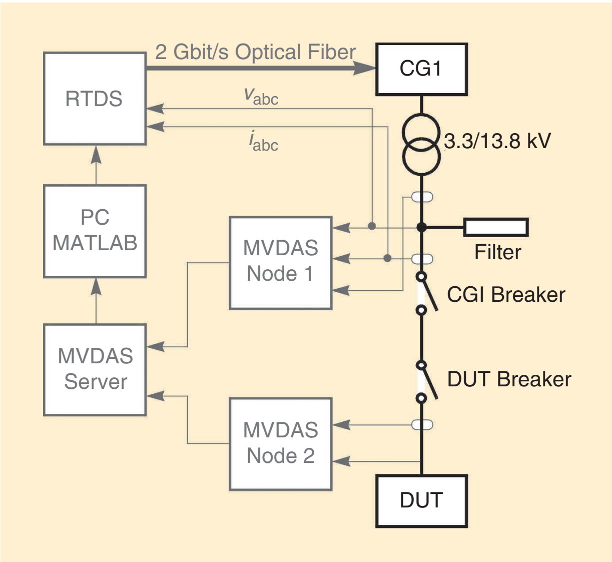

Figure 12. The impedance measurement system at NREL. RTDS: Real-Time Digital Simulator; DUT: device under test; MVDAS: medium-voltage data acquisition system.

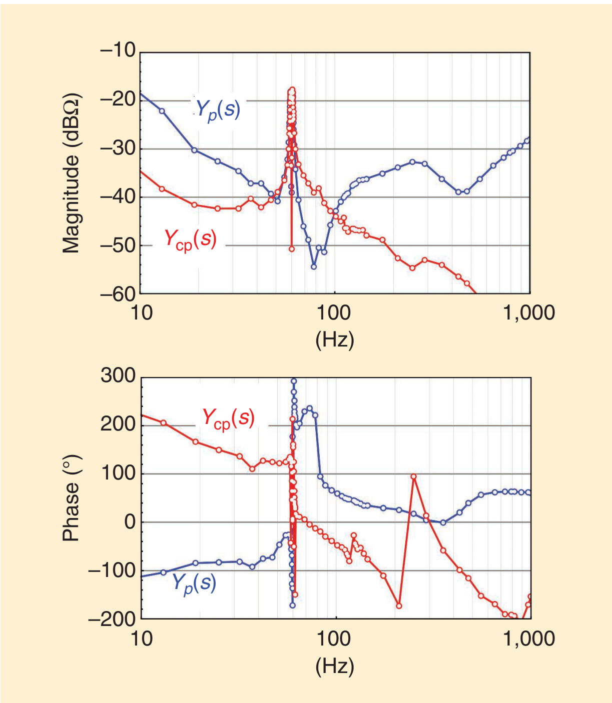

Figure 13. The sequence admittance measurements of a 1.9-MW wind turbine at NREL.

Measurement Using CHIL Simulations

In a CHIL simulation platform, the control hardware consists of controller interface circuits and industrial controllers, where electrical system control algorithms are executed. The control system receives operating commands, processes feedback signals, and sends out control signals—such as PWM signals and circuit breaker commands—to the power-stage circuits simulated in a RTDS. Simulated power-stage circuits include models for the electric grid, wind turbine generators, power electronics converters, harmonics filters, circuit breakers, and other passive components. Figure 14 presents a CHIL real-time simulation system at General Electric Research. It facilitates control algorithm development and time-domain performance evaluation for different power electronics systems. The control interface boards for different converters (shown in the figure for wind turbines, HVdc converters, and PV inverters) are modified to interface with RTDS GTIOs. Note that, compared to a real system, the CHIL platform introduces additional control delays because of computational delays and I/O conversion delays, whose effects on the simulation results must be carefully evaluated and addressed.

The impedance responses of IBRs can be calculated from analytical models based on simplified control and circuit models. The analytical models are valuable during the control design phase because they reveal key design factors that dominate the system impedance responses. However, during the test and validation phase, when more-accurate impedance responses are required, it becomes extremely difficult to develop the analytical models for system-stability analysis due to complex control algorithms and high system nonlinearity. The impedances can be measured at a grid simulator

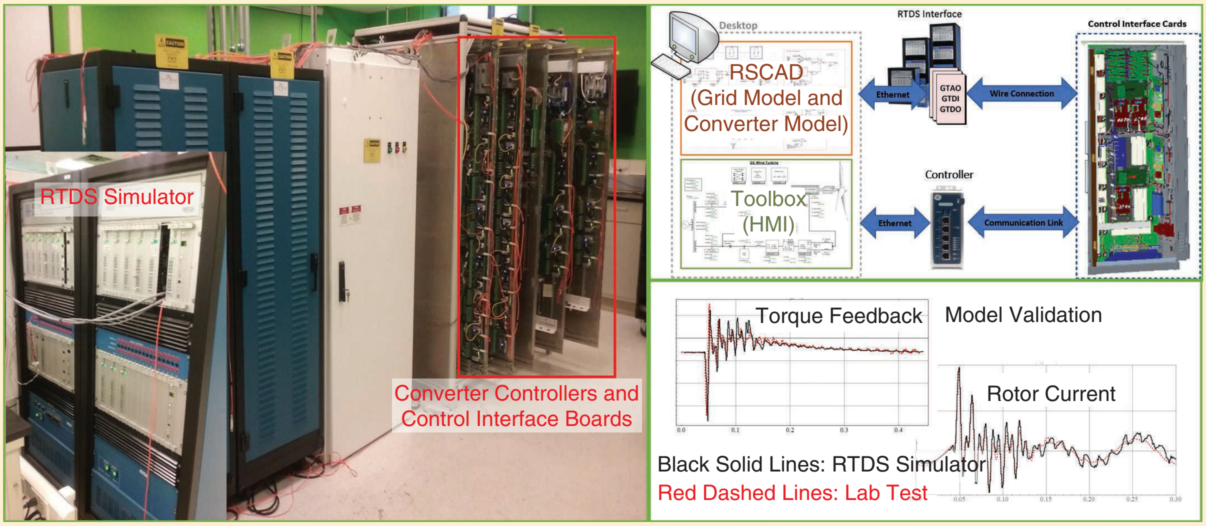

Figure 14. The CHIL real-time simulation platform for grid integration tests. HMI: human–machine interface; GTAO: Giga-Transceiver Analogue Output Card; TDI: Giga-Transceiver Digital Input Card; GTDO: Giga-Transceiver Digital Output Card. (Source: GE Research).

facility, as described previously, but the testing costs could become prohibitively high for vendors because many impedance tests might be required during the control development stage. The CHIL real-time simulation platform becomes a cost-effective solution for the testing and validation of the frequency-domain impedance responses of IBRs. It has high accuracy and fidelity because the control replica remains intact compared to the real system while the power stage and sensors are carefully modeled in a digital simulator. Figure 15 illustrates the positive-sequence impedance response of a 5-MW Type 3 wind turbine, obtained using the CHIL platform and real turbine controller. The obtained impedance response can be used for the design validation of a single wind turbine and for system-stability evaluations by wind farm system operators.

Measurement Using Dynamic Events

It is possible to use voltage and current measurements during dynamic events to estimate the impedance response. Dynamic events might excite nonlinearities in IBRs or might not contain sufficient energy in voltage and current signals at all frequencies—both of which might introduce errors in the small-signal impedance estimation. However, a dynamic event, data-based approach for impedance estimation can be accurate at low frequencies. In their 2020 article, Fan and Miao designed a method to derive s-domain expressions of time-domain voltage and current measurements during dynamic events using subspace methods, such as the eigenvalue realization algorithm and dynamic mode decomposition. The derived s-domain expressions can be used to estimate the impedance response. Such methods can also be applied in conjunction with advanced machine learning

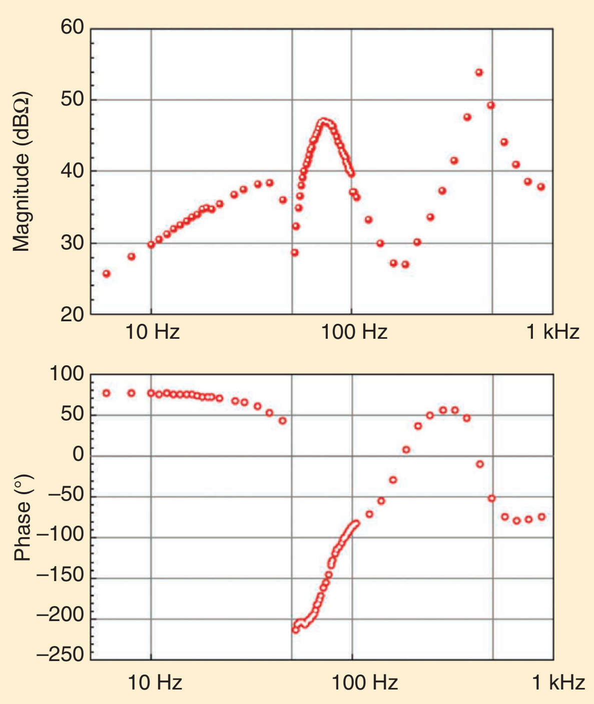

Figure 15. The positive-sequence impedance response of a 5-MW wind turbine obtained using the CHIL platform. (Source: GE Research).

algorithms on phasor measurement unit data for impedance estimation at different nodes in a power system network to monitor system stability in real time.

Future Development: Grid-Level Stability Studies

On one hand, model-based tools that have been used for decades for the small-signal stability analysis of bulk power systems are becoming ineffective in understanding the stability characteristics of modern power systems with very high levels of IBRs. On the other hand, while the impedance method can efficiently represent the stability behavior of IBRs without depending on their open-box models and is increasingly used for the stability analysis of large power electronics systems, its scalability for doing interconnection-level stability studies remains questionable. The combination of state-space modal analysis, based on the phasor models of conventional synchronous generation and transmission network, with impedance analysis, based on the impedance responses of IBRs, can overcome the limitations of both of the stability analysis paradigms. Such a combination can be supported by emerging cosimulation tools that can simulate modern power systems by interfacing the positive-sequence phasor simulation models of bulk power system with the EMT simulation models of IBRs. Figure 16 depicts this new paradigm of using cosimulation with positive-sequence phasor and EMT models and the combination of impedance analysis and state-space modal analysis with impedance analysis methods for the stability analysis of modern power systems.

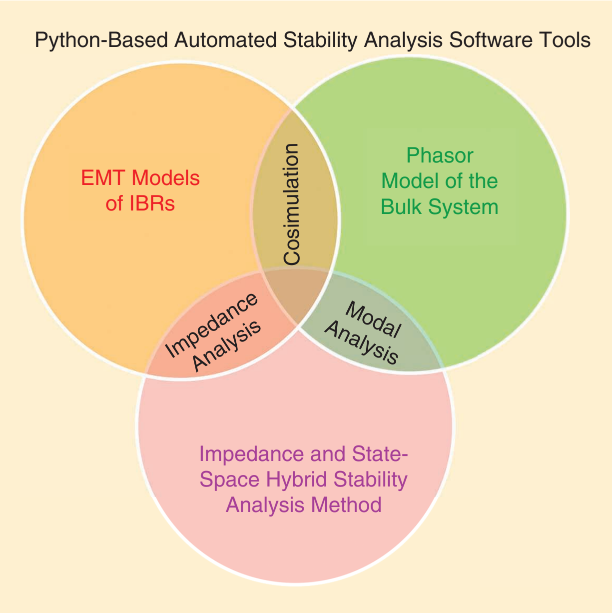

Figure 16. The stability analysis tools for power systems with high levels of IBRs.

Because grid-level studies using impedance methods can be time consuming, it is important to develop automation tools for performing impedance-based stability analysis. Figure 17 illustrates python-based, automated impedance-scanning and stability-analysis tools developed at NREL. These tools can work on vendor-supplied, black-box EMT models of IBRs, such as wind turbines, PV inverters, and HVdc converters, to scan their impedance response for performing stability analysis for different grid conditions.

One key hurdle in combining the data-based impedance-analysis approach with the model-based, state-space, modal-analysis approach is the development of s-domain analytical models of IBRs from their impedance or admittance responses. This can be

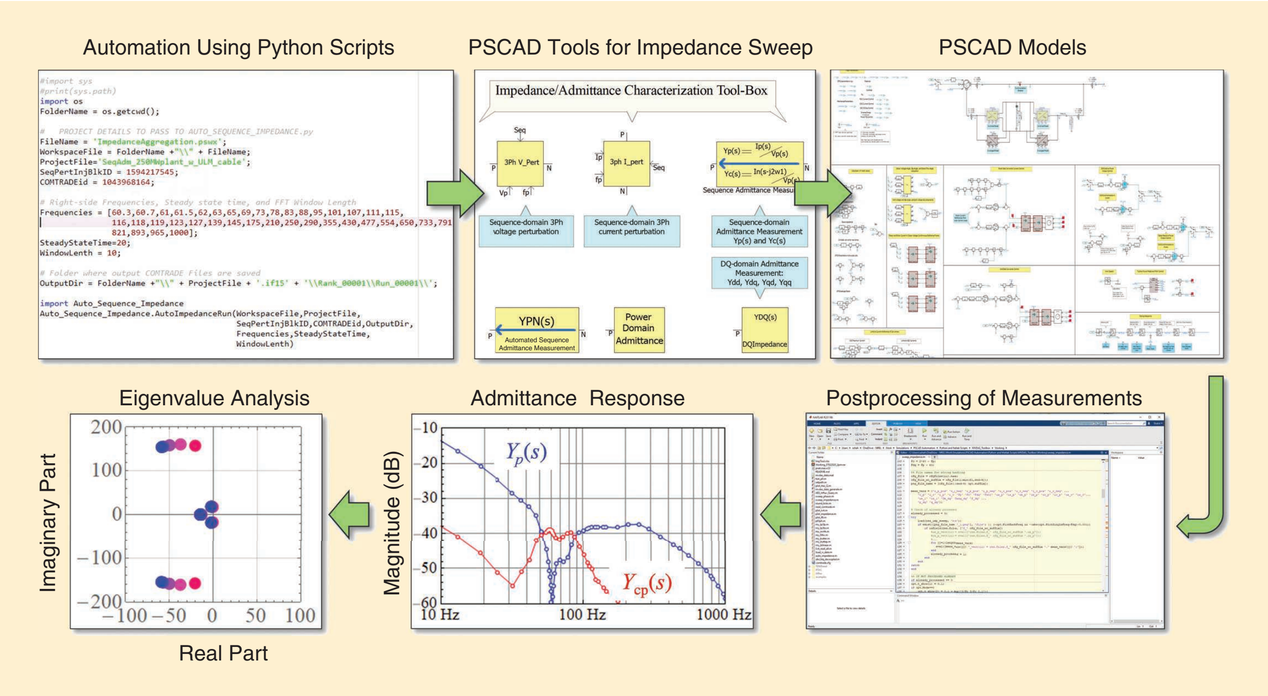

Figure 17. The automated impedance scanning and stability analysis tools for PSCAD studies. PSCAD: Power Systems Computer Aided Design.

achieved by doing frequency-domain curve fitting of impedance or admittance responses, as demonstrated by Fan and Miao in 2020. The combination of impedance and modal analysis can not only evaluate the stability of power systems with very high levels of IBRs, but it can also show the participation of various IBRs in a particular stability mode.

Conclusion

As the complexity of power system dynamics continues to grow because of ever-increasing levels of IBRs, on one hand, the existing model-based tools are becoming ineffective in evaluating the stability problems in modern grids, and, on the other hand, new types of stability problems that appear over a wide range of frequencies are becoming more common because of control interactions in IBRs. Data-driven tools are necessary for analyzing modern power systems. This article identified one such tool, the impedance approach, for analyzing the impacts of IBRs on the stability of power systems. After giving an overview of the impedance methods, we described the growing number of applications where they are used for stability analysis, ranging from microgrids and shipboard power systems to wind and PV power plants with high-voltage ac and dc transmission networks used for integrating large amounts of renewable generation. We also focused on different methods for obtaining the impedance responses of IBRs, including direct measurement using a grid simulator; CHIL simulations; the dynamic-event, data-based approach; and estimation from black-box EMT models. Impedance methods have proven to be effective for the analysis and mitigation of stability problems in wind and PV power plants, including offshore wind energy systems using either high-voltage alternating current (HVac) or HVdc transmission to the grid. New research on and developments in the impedance methods are happening now to make them suitable for grid-level stability studies. This research is addressing key hurdles through combining the impedance methods with modal analysis approaches and developing automation tools.

Acknowledgments

This work was authored in part by the Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding was provided by the U.S. DOE Office of Energy Efficiency and the Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

For Further Reading

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