Powering the future

Navigating the challenges of integrating renewable energy into utility grids

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As the world pivots towards sustainable energy solutions, the integration of renewable energy sources into existing utility grids has become a central concern.
As the world pivots towards sustainable energy solutions to combat climate change, the integration of renewable energy sources like solar photovoltaics (PV) and wind into existing utility grids has become a central concern. This white paper delves into the complexities and challenges that accompany this transition. It highlights the remarkable growth in renewable energy capacity, driven by significant technological advancements and cost reductions.

However, this growth is not without its challenges. One of the key issues is the complexity of integrating all renewable energy sources into the utility grid while maintaining grid stability and reliability to prevent energy disruptions affecting consumers.

Collaborative solutions
On top of the wind industry’s inherent limitations, some of the other challenges include the technological advancements required for inverter-based generation (e.g. grid forming, black start), a need to evolve grid connection codes for new technologies and distributed generation, the intricacies of modeling and simulation, and the need for improvements in grid compliance processes to ensure safe, reliable, and efficient operation of transmission and distribution grids.

These challenges require close collaboration between equipment manufacturers, developers, grid operators, and regulatory bodies to ensure a seamless and efficient transition to a sustainable energy future. This paper provides an in-depth analysis of these challenges and offers insights and solutions to pave the way for a greener, more resilient energy landscape.
To reach the Paris Agreement with maximum global temperature increase of 1.5°C, the IEA estimates that a total installed renewable energy generation capacity of around 11000 GW would be needed by 2030 which triples existing global renewable generation today. Growth of renewable energy generation over the last decade has been impressive, achieving continual record levels in terms of newly added capacity and increasing renewable energy penetration into the global energy pool. As per IRENA statistics, during 2022 almost 83% of all newly added global electricity capacity has been renewable plants and, among all renewable energy sources, hydro (21 GW), wind (75 GW) and solar photovoltaic (PV) (191 GW) have been the leading renewable technologies. As per IEA analysis and forecasts, in 2023 renewable energy generation capacity increased by almost 50% to an estimated record high of 507 GW, where 75% (380 GW) corresponded to solar PV.

1. IEA (2023), Net Zero Roadmap A Global Pathway to Keep the 1.5 °C Goal in Reach
2. IEA (2024), Renewables 2023 Analysis and forecast to 2028
...the Levelized Cost of Energy (LCOE) of renewables has significantly reduced over the last decade, positioning it as the most competitive source of any new generating power.
Levelized Cost of Energy

The renewables expansion has been possible due to a combination of internal factors, such as technology maturity, which have led to significant reduction of the Levelized Cost of Energy (LCOE), positioning renewable energy as the most competitive source of energy. Moreover, this growth has been facilitated by various external factors, including the high prices in the global energy market, and rising fossil fuel prices, which are a result of geopolitical instabilities. Additionally, decarbonization policies aimed at complying with the Paris Agreement have laid the foundation for the widespread adoption of renewable energy generation. Among all renewable energy sources, onshore wind and utility-scale solar photovoltaics (PV) have become more popular due to their lower LCOE of 0.033 USD/kWh for onshore wind and 0.049 USD/kWh for solar PV. These costs are significantly lower than those of the least expensive fossil fuel plants, including combined cycle gas turbines or coal-fired plants, which have an LCOE of around 0.069 USD/kWh. However, other renewable options like hydro, concentrated solar power (CSP), offshore wind, biomass, and geothermal are also attractive. Their LCOEs range from 0.06 USD/kWh to 0.11 USD/kWh, still competitive when compared to fossil fuel plants. Depending on the project and region, there is a significant variation in LCOE.

4. IRENA (2023), Renewable power generation costs in 2022, International Renewable Energy Agency, Abu Dhabi
All these renewable energy sources can be categorized into two groups. The first includes renewable sources that, as part of their technology, employ a large rotating generator and/or thermal processes, such as conventional generation that includes hydro, solar CSP, biomass or geothermal. The second comprises the renewable resources that use inverters as part of the conversion or control process, such as solar PV, and onshore and offshore wind. The latter are in focus due to the challenges and potential implications for integrating them into the grid.

**Solar plants**

Utility-scale solar PV technology has grown the most and, depending on the country, taken over up to 50-70% of renewable energy generation new capacity. PV panel cost reduction is the main reason for this. LCOE has decreased more than 85% over the last decade and is expected to decrease even more in the coming years through technological innovation and manufacturing optimization – a key aspect of this being modularity. Typical commercial PV modules range from 50 kWp to 500 kWp and are manufactured in large facilities to obtain economy of scale advantages, enabling OEMs to build large-scale plants by stacking multiple PV modules in series. Component modularity enables a diverse application spectrum from large utility-scale plants to small residential or industrial rooftop applications. The size of utility-scale PV plants has increased progressively over the last decade, breaking capacity records from early 100 MW to the latest 2000 GW projects.

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5. IRENA (2023), Renewable power generation costs in 2022, International Renewable Energy Agency, Abu Dhabi
Onshore wind

Today, onshore wind is a powerhouse based on the technology maturity obtained through the last decades of continuous development and beneficial governmental policies (e.g., feed-in tariffs) which allowed the industry to blossom. However, there has been fierce competition and massive cost reductions over the last decade that enabled onshore wind to become one of the most competitive renewable energy generating sources without any subsidies. Spectacular growth in turbine size from hundreds of kilowatts to the latest versions ranging 5-6 megawatts allowed the industry to grow from small distribution-connected plants of just a few turbines to massive large-scale utility plants with hundreds or thousands of megawatts. Wind technology as opposed to solar PV requires large infrastructures for development projects in terms of equipment procurement, logistics and installation.
Offshore wind

Offshore wind capacity in the North Sea in Europe has already been deployed massively over the last decade. Shallow seas available in these locations enabled offshore wind farm developers to adapt onshore wind technology and install it on bottom-fixed technology (monopiles, jackets, gravity or tripods) and test innovative concepts such as VSC-HVDC (voltage source converters – high voltage direct current) transmission to address some of the long-distance transmission challenges. Competition over the last decade has increased turbine size from a few megawatts to around 15-20 MW based on the latest OEM next generation turbine announcements. During that period, the LCOE decrease for technology has been impressive, however it is still not at the same level of competitiveness as solar PV and onshore wind technologies for a massive rollout.

Global offshore development plans are ambitious considering short-term decarbonization timelines, however, most of the relevant locations for large-scale rollout are located in deepwater environments. Offshore floating technology required for such conditions is not yet mature and concept designs continue being developed and deployed in demo sites for demonstration purposes but are still far from being released on large-scale commercial projects.

Competition over the last decade has increased turbine size from a few megawatts to around **15-20MW**
Figure 2: Composite graph depicting the growth of renewable energy generation over time alongside the decreasing Levelized Cost of Energy (LCOE) for different types of renewable sources, emphasizing the increasing affordability and adoption of renewable energy technologies over the years.²,⁶
Fierce competition in both onshore and offshore wind technology is leading OEM manufacturers to develop new products not long after the previous versions to stay ahead of competition. Product development typically relies on scaling existing technology, however large turbine sizes and power increases require major design changes in many areas. This results in short product development, testing and validation cycles, which can lead to quality issues within products or fleets and ultimately higher costs. Consequently, this does not provide OEMs with consistent returns on investment.

Development phases are often shortened to expedite product releases to the market, with a primary focus on cost reduction from the outset. A diminished labor force is under pressure to develop products in a rush, test products according to strict timelines and, at the same time, resolve the quality issues of previous product platforms. Additionally, external geopolitical factors are undermining wind OEMs’ financials due to increases in interest rates, inflation, raw materials, and supply chain constraints; neither of those conditions seem to be going away in the short term in what is a growing industry.

**Technological shift**

In addition to massive renewable energy integration, utility grids have faced an unprecedented technological shift. Traditionally, large conventional generating stations delivered energy through Transmission and Distribution (T&D) infrastructure to either residential, industrial, commercial or transportation consumers. Transmission Service Operators (TSOs) only needed to adjust generating stations’ production or reduce consumption through load shedding schemes to balance the grid.
Nowadays other technologies are being introduced extensively into the large utility grids, such as distributed PV generation, electrification of transportation with electric vehicles (EV), storage systems for renewables energy management and microgrids.

**PV panel growth**
The lowering of PV panel prices has encouraged unparalleled growth in small-scale self-consumption applications in both industry and households which, in some countries, is reaching peaks of more than 70% of all energy generated.

**EV charging demands**
Electrification of transportation with the objective of reducing excessive CO2 levels in major cities or densely populated areas is leading to huge demands for energy and, in many instances, this was not planned for during the design of distribution infrastructure.

**Storage technologies**
The popularity of storage system solutions for balancing the unpredictability of renewable energy sources, such as wind and solar PV, is increasing due to the declining prices of battery systems. These storage technologies are integrated into renewable energy plants primarily to maximize revenue through market schemes and fluctuations in energy prices. Additionally, storage systems can offer grid services to enhance grid stability. On the other hand, micro-grid architectures trying to achieve “Net Zero Energy” or neutral energy balances within residential buildings, industrial or community areas are also increasing in popularity through self-sustainable designs. Those designs aim to minimize energy consumption and produce energy through self-consumption solar PV generation which, under normal circumstances, will decouple those installations from the main grid.

**Balancing the grid**
The introduction of all those technologies has a great impact on the utility grids of Transmission Owners (TOs) and Transmission System Operators (TSOs) in terms of planning, operations, market, reliability, and maintenance. TOs/TSOs have been gradually modifying grid codes to require that new renewable energy plants possess additional capabilities. These enhancements aim to improve the ability of TOs/TSOs to control and balance the grid. As a subsequent measure, grid codes must be improved to require additional features and mechanisms that can support the expanding industry as a result of an increase in distributed photovoltaic (PV) generation, battery systems, and electric vehicles (EVs).
The lowering of PV panel prices has encouraged unparalleled growth in small-scale self-consumption applications in both industry and households.

Electrification of transportation is leading to huge demands for energy which was not planned for during the design of distribution infrastructure.
The challenges

Grid integration challenges can be catalogued into two main areas: generating plants and utility grids (Transmission System Operators - TSOs and Distribution System Operators – DSOs). Additionally, electrical modeling is common to both.
In terms of generation, the focus of those challenges today are based primarily on inverter renewable plants using technologies such as wind and solar PV, due to the expected growth of those two technologies. This paper specifically covers the challenges of wind turbine-based plants, due to the greater complexity of wind turbine technology and its mechanical/structural and electrical dynamics compared to solar PV.

Mitigating loads
Modern wind turbine technology primarily utilizes Type 3 (Doubly Fed Induction Generator, DFIG) or Type 4 (Full Power, FP) architectures. These systems convert mechanical energy captured by the turbine blades into electrical energy, using associated generators and inverters, either fully or partially. The inverters, along with the park-level controller, are crucial in providing the necessary features, performance, and interfaces required by TSOs/DSOs. Traditionally, efforts from wind OEMs have focused on looking at those controllers (inverters and park level controls) to assess compliance with grid code requirements. However, turbine controllers have gained importance recently due to the grid’s demand for stricter and quicker response times, as well as the challenges larger turbine sizes present to mechanical and structural integrity in meeting these requirements. Advanced turbine control algorithms have been developed to mitigate loads on critical components while reducing the impact of upscaling in terms of cost. Although those are primarily mechanical controllers, there are some undesired mechanical or controller interactions which are passed on by inverters and plant level controllers to the grid. Most of those constraints primarily affect active power control and its required capabilities from TSOs/DSOs under normal and abnormal operation.
Figure 3: Schematic representation of a wind turbine's control system and its components, showing the interconnected roles of tower dampers, the turbine controller, and the drive train damper in managing the dynamics of a wind turbine.
Typically, the International Electrotechnical Commission (IEC) guidelines for verifying wind turbine loads are based on a variety of factors. These include different wind profile configurations, the operational status of the turbines, and various environmental or logistical conditions. Electrical grid characteristics are only briefly tested (e.g. grid faults) which is clearly insufficient considering the growing demand for different features and performance levels required by TSOs/DSOs.

As part of the internal design process, wind OEMs must execute the necessary additional testing, but complexity and the time needed to execute them is significant due to the wide variety of grid requirements, setups, and parameter configurations required globally. Furthermore, the internal simulation toolchain that OEMs use for load assessments is complex to develop because it integrates various disciplines, including aerelastic, mechanical, and electrical capabilities.

Figure 4: 5 examples of controller interaction and mechanical/structural limitations.
Another challenge is the need to represent all those mechanically driven dynamics and constraints in grid modeling. Typically, OEM grid models to date only consider some mechanical limitations in terms of maximum and minimum active power ramps and limits under normal operation or abnormal operation (e.g. voltage dip) additional to the inverter-based controllers or park level controllers. However, adverse grid interactions, such as mechanical resonances or forced oscillations observed in recent years, were not initially accounted for. Today, TSOs/DSOs require these issues to be addressed in the models. Ultimately, all turbine characteristics that affect the grid should be accurately represented in the electrical models provided to TSOs and DSOs.

**Grid forming inverters**

Apart from mechanical constraints and the turbine dynamics of larger wind turbines, there are also other electrical design challenges for wind turbines and their equipment. In terms of product design, one of the major focusses today is developing generating plants capable of generating the grid – the so-called grid-forming inverters. Grid-following inverter-based architectures - where grid frequency synchronization is performed through Phase Locked-Loop (PLL) algorithms - are being replaced with grid-forming architectures, where voltage and frequency are directly controlled by inverters.

Multiple architectures are available for grid-forming controllers, however, they still need to be deployed, tested and later standardized within grid connection codes to enable an extensive rollout. To date, only a few countries have developed a subset of minimal requirements for grid-forming inverters, which will need to be tweaked after testing and lessons learned.
Compliance testing

Another challenge is directly linked to compliance testing either at OEM- or plant level. Traditionally, OEM wind turbine grid compliance testing has been performed at demo or testing sites with large certification and validation campaigns based on international standards (e.g. IEC61400-21) or local standards (e.g. FGW- Fördergesellschaft Windenergie und andere Dezentrale Energien e.V.). Within those testing campaigns both electrical capabilities and control performances against those standards are checked, and in addition, extended testing and field data collection is traditionally used for testing broader electrical capabilities, control performances or for validating grid models. Those testing campaigns can take months or years to finalize with dedicated teams and external companies, so the cost is huge for wind OEMs.

Alternative test options

In order to reduce time and cost, wind OEMs are evaluating alternative options in order to fragment the process and use test benches for partial or even complete validations. While still in draft, the new IEC61400-21-4 offers some options for test bench set-ups (e.g. standalone inverter, nacelle bench and/or grid/generator emulators), and potential validations for each of those. The challenges of those set-ups include controller interactions between grid emulators and turbine inverters or generator emulation for certain controllers (e.g. pitch controller). In terms of plant level testing, traditional plant level grid testing is based on plant level controllers (frequency, active power, and voltage/power factor (PF)/reactive power controllers) where wind turbine capabilities are partially tested in terms of product capabilities and response times/accuracies. This testing is not expected to change, however the challenges associated with a predominant inverter-based grid remains as well as all the interactions and instabilities that will likely continue to be observed at this stage.
The challenges;

**TSO/DSO**

TSOs/DSOs face different challenges depending on the time scales and applications.

Figure 5: depicts the flow of energy from a Transmission System Operator (TSO) to a Distribution System Operator (DSO) and ultimately to various types of consumers and illustrates the relationship and energy transfer between the high-level transmission system and local distribution networks.
**Renewables grid support**

In the short-term conventional and renewable energy generation will coexist to deliver energy to end-consumers and will have different responsibilities in terms of grid stability and reliability. In many countries, renewable generation already produces, or will produce, the bulk of the power while conventional generation is used to cover any gap in demand or as a back-up to provide ancillary services that renewable generation cannot provide today.

Renewable energy generation can be categorized into "old" technology, which is nearing the end of its lifespan, and "modern" technology that is currently being installed. Modern renewable generation technologies offer advanced grid support features, such as extended reactive power (PQU) capabilities, synthetic inertia, symmetrical and asymmetrical fault current support, fast frequency control, and power oscillation damping. In contrast, older renewable plants either do not support these features or only provide very basic functionalities. These basic functionalities, defined in grid connection codes a decade ago, include fundamental fault ride through (FRT) capabilities, slow active power control schemes, or slow power factor control. Therefore, modern renewable generation is going to be key to supporting TSOs/DSOs to maintain grid stability and reliability, while conventional generation, either in operation or as a back-up, will provide some of the services which cannot be done today by modern renewables generation (e.g. black start or to provide fast frequency control in case of falling frequencies).
Despite significant advancements, the widespread integration of renewables remains a concern for TSOs/DSOs as unlike conventional generation, new renewable energy installations lack large-scale inertia and significant fault current contributions, essential for grid stability and operation. The absence of adequate inertia could weaken the grid and interconnected systems or lead to more frequent large-scale frequency deviations. Consequently, TSOs and DSOs are prioritizing the inclusion of ancillary services that enable rapid frequency control schemes to address these challenges. Similarly, conventional power generation contributes significant short-circuit currents, a capability limited in renewable generation by inverter technology. As new generation sources are integrated into their grid areas, TSOs/DSOs must conduct thorough planning and impact studies. This involves detailed system modeling and simulations to assess the implications of these additions.

**Integration challenges**

In the long term, a significant challenge is the full transition from large conventional generation facilities to renewable energy sources that use inverters. As conventional power plants are phased out, TSOs and DSOs will need renewable energy plants or other supporting technologies connected to the grid to replicate the capabilities previously provided by conventional generation. For example, these capabilities would include black start or primary frequency control specifically for under-frequencies where storage system solutions play a key role. However, that might not be cost effective or necessary for all generating plants due to the higher investment needed to enable it.
Some solutions tested in recent years include hybrid renewable plants where wind and/or solar PV are combined with storage solutions, primarily for energy management, but which could also be used to provide grid services such as primary frequency control or black start. Synchronous condenser solutions are already being used to support weak grid applications by providing additional short-circuit current contribution, inertia, or voltage/reactive power support. Standalone battery storage facilities are being developed to support the grid with primary frequency control. Flexible alternating current transmission systems (FACTS) are being employed for fast additional reactive power capability or fast voltage control at specific points within the system.
Challenges:

Generating grid

Inverter-based renewable generation with grid-following architecture (PLL synchronization) cannot generate frequency and voltage by itself.

Inertia

Renewable generation based on an inverter has no inertia like conventional generation and therefore cannot limit quick changes on frequency, jeopardizing grid operation and stability.

Black start

Inverter-based renewable generation systems using grid-following architecture (PLL synchronization), without long-term energy storage, cannot self-power during grid outages.

Figure 6: Challenges and potential solutions
Large renewable energy plants connected to the grid, either through long transmission lines or within isolated grid systems, may experience weak grid conditions. These conditions present significant challenges to maintaining grid stability during and after grid faults, especially for inverter-based renewable generation that utilizes a grid-following architecture.

**Harmonics**

The harmonic content of inverter-based renewables is higher than that of conventional generation, owing to the practice of switching devices and their control patterns. This not only affects power system equipment, such as transformers, due to the increased harmonic content, but also because of the system resonances excited by these harmonics.

**Weak grid operation**

**Short-circuit currents**

Inverter-based renewables provide lower short-circuit currents (limited by inverters) compared to conventional generators. This has an impact on grid support during faults and protection schemes.

Figure 6: Challenges and potential solutions
**Grid forming**

New inverter-based architecture which directly controls voltage and frequency through closed-loop controllers up to the inverter’s limits. This architecture allows inverter-based generation systems to support the grid in various operational modes, including normal functioning and black start scenarios. Simultaneously, it can provide inertia or inherent primary frequency regulation, akin to what conventional generators offer. It also enables weak grid operation.

**Storage**

Long-term energy storage enables inverter-based generation to self-power when there is no grid available (black start). Additionally, it can be used as a balancing energy management mechanism or, in the case of fast storage systems (e.g. batteries), to provide reserves or primary frequency control for under frequencies. Additionally, other grid supporting features could be implemented on fast storage system solutions, such as fault support.

**HVDC transmission**

Renewable generation hubs transmitted through HVDC-VSC transmission links improve controllability by decoupling those plants from the grid. Inverter-based HVDC transmission enables flexibility on the grid through multiple supporting features enabled within those devices.
Flexible alternating current transmission systems (FACTS) supports the grid by providing reactive power and fast reactive/voltage control. Enhancing reactive power capabilities, both during steady-state operation and fault conditions by supporting voltage at various grid points, improves controllability and enhances voltage stability.

Synchronous condensers

Synchronous condensers are used widely to support large, short-circuit currents on weak grid applications. Additionally, they can provide reactive power to control voltages.
Adapting grid codes

As power systems evolve, grid codes must be updated accordingly. Over the years, TSOs/DSOs have been anticipating an increase in renewable generation penetration into their power systems by introducing stricter requirements in grid connection codes for inverter-based renewable generation. These requirements stem from detailed interconnection and planning studies conducted by TSOs/DSOs with the purpose of guaranteeing that within their areas of control, TSOs and DSOs have sufficient mechanisms in place to maintain the power system's reliability and security.

Streamlining grid connection

At the same time, the process to connect any generating plants has become more complex to ensure that upon connection there is not going to be any deviations to any required plant capabilities compared to performances shown in simulation models. This process outlines a sequence of steps and necessary deliverables at each stage to achieve specific milestones, such as plant energization or the commencement of commercial operations. Those steps change from country to country but usually include equipment certification, simulation models, validation requirements, and commissioning and post-commissioning testing to ensure all grid code requirements are properly assessed before connection and during the entire operating life of the installation. Depending on the country, this detailed connection process is either already in force or going to be adopted shortly.

Advancing grid standardization in Europe

Europe took a big leap forward with the standardization and harmonization of grid requirements through the ENTSO-E connection codes released in 2016, however other countries are still behind on implementation of harmonized and updated requirements and connection procedures. The grid connection and grid compliance processes have become major focal points for any new or upgraded plant installation due to the complexity and demanding engineering capabilities required throughout every project's lifecycle.
Figure 7: The three key operational notifications required for a power-generating facility's integration into the grid

**Energization Operational Notification (EON)**

An EON entitles the power-generating facility owner to **energize its internal network and auxiliaries** for power-generating modules by using the grid connection that is specified for the connection points.

- Itemized statements of compliance
- Updated applicable technical data
- Simulation models and studies, including the use of actual measured values during testing

**Interim Operational Notification (ION)**

An ION entitles the power-generating facility owner to operate the power-generating module and generate power by using the grid connection for a limited period.

- Updated itemized statements of compliance
- Detailed technical data on plant-relevant components for the grid connection
- Equipment certificates issued by an authorized entity, certified in respect to plant modules
- Simulation models, as required by TSOs/DSOs
- Simulation studies demonstrating steady-state and dynamic performance
- Compliance tests

**Final Operation Notification (FON)**

A FON entitles the power-generating facility owner to operate a power-generating module by using the grid connection.

- Updated itemized statements of compliance
- Updated applicable technical data
- Updated simulation models and studies, including the use of actual measured values during testing
Adapting grid connection codes for new technologies

All code updates today are intended for large generating plants that connect to the transmission grid. However, in many countries there has been tremendous growth in small scale solar PV generating units which in some countries’ zones may reach even 70-100% of the overall generation during certain periods of the day or year.

Given the size of these installations, grid connection codes either do not require or only demand minimal support from them for balancing the utility grid. The same is true for storage-based solutions (e.g. batteries) or even electrical vehicles whenever they act as generators and deliver energy to the grid. TSOs/DSOs will need to monitor the impact of these new technologies in terms of controllability, stability, and reliability and, if needed, introduce more stringent connection and compliance rules for this type of installation going forward.
Over the years, as inverter-based generating plants increased in volume and size, TSOs have been increasing their demands in terms of plant modeling and the required simulations for those plants. Inverter-based generation operation and dynamics complexity is higher than those of traditional generation and that is why detailed modeling is key to assessing power system stability and very fast dynamics under all operating modes from plant and grid perspectives.

**EMT modeling for detailed inverter dynamics**

For large inverter-based plants which might have a high impact on the grid, electromagnetic transient (EMT) modeling and study work is predominant today. EMT models (e.g. PSCAD, EMTP-RV) are characterized by detailed switching device models and embedded inverter controls, which perform at microsecond (µs) timescales to capture any fast switching transient.

EMT models allow checking behavior for normal and abnormal inverter operation and fast switching surges, and also to capture any interactions with other controllers. However, for evaluating transient stability, typically aggregations are required due to the timescales and computational burden. Although EMT simulations are optimal for analyzing inverter dynamics, assessing system stability in time-domain platforms requires an impractical number of iterations. Consequently, frequency-domain models are commonly employed to identify critical regions of inverter operation, thereby reducing the number of necessary iterations. A root-mean square (RMS) model benchmark with EMT models is required to be submitted as part of the connection and compliance process to TSOs.

**RMS modeling for power system evaluation**

Submitting RMS models, such as Power System Simulator for Engineering (PSS/E) and Power Factory, has been a mandatory requirement for many grid connection codes for years due to TSOs’/DSOs’ need to evaluate large-scale system steady-state operation and transient stability. RMS models are characterized by averaging models of inverters, allowing them to perform at millisecond time-scales, however they are unable to capture sub-transient behavior or fast controller interactions. Since RMS models are averaged, the benchmarking process using EMT simulations is complex. TSOs require many iterations to match dynamics as closely as possible, considering the limitations of standard library models or custom-made models provided by OEMs.
Figure 8: Illustration of the spectrum of modeling techniques used for grid integration, categorized by their time scales and associated control type or phenomena.
For small scale projects, which don’t greatly impact on the grid, TSOs today typically do not require EMT models which simplifies the process. Only RMS modeling and associated grid studies are required to connect to the grid as per applicable grid codes, however this might change as the penetration of renewables grows.

**Power quality**

Another major modeling area of interest for inverter-based generation is power quality – particularly harmonic emissions. Commercially available inverters for wind and solar PV usually use 3-level topology with different types of pulse width modulation (PWM) patterns which introduce large quantities of harmonic levels that are typically filtered through passive low-pass filters after the inverters. To avoid any passive filters afterwards, some modern inverters employ optimized pulse patterns to minimize the harmonic emissions at certain frequencies.

**Harmonic models**

Harmonic models have traditionally been required by plant owners and TSOs/DSOs for verifying inverter emissions, developed from field data gathered in IEC measurement campaigns. The IEC 61400-21 standard mandates measuring harmonic emissions at various active power levels, without reactive power and at normal operating voltage, which are typically considered the standard operating points for generation.

While this approach was sufficient a decade ago when generators did not support short-term voltage regulation and stability, the growing reliance on renewables has led to weaker systems and grids. Consequently, inverters are increasingly expected to operate outside these “normal” conditions, necessitating adjustments to traditional measurement and modeling practices to accommodate the changing dynamics of power systems. The emissions of harmonics from inverters are mainly influenced by the voltage at their terminals, their switching strategies, and the effectiveness of any passive harmonic filters in reducing or canceling these harmonics. It is essential to measure harmonic emissions across all operating points along the PQU curve to ensure that the worst-case harmonic levels are identified and assessed.

**Harmonic impedance**

Another important aspect to consider for harmonic emissions is to completely characterize the inverter impedance, which in many relevant regions might show negative resistances and amplify those harmonic emissions afterwards. This is especially a challenge in offshore projects, where the large capacitance of offshore cables used for connecting turbines significantly decreases the resonant frequencies to critical regions below the 20th harmonic. As a consequence, obtaining accurate harmonic emissions and impedances is key for modeling inverter-based emissions and for validating those in a controlled environment without any external background harmonics such as test benches or SIL/HIL (Software in the Loop/Hardware in the Loop) setups.
Detailed modeling is key to assessing power system stability and very fast dynamics under all operating modes.
Conclusion

Renewable energy generation is imposing challenges on generation plants integration and TSO/DSO grid infrastructure. As with any other emerging technologies, it needs time to stabilize technologies, build any required infrastructure and to prepare the labor force required to tackle those challenges.

Effective collaboration among OEMs, developers, owners, operators, and TSOs/DSOs is key to ensuring renewable generation develops and achieves the required technology maturity level. Engineering expertise plays a vital role in addressing these challenges through ongoing product development, informed by lessons learned from extensive product testing and validation.
About DIS/CREADIS

With over 25 years of engineering experience in the renewable energy sector, DIS/CREADIS is well-positioned to help you overcome the unique challenges of this industry. We acknowledge the intricate nature of grid integration and the design of electrical infrastructures and offer our expert advice to ensure your renewable power asset is effectively incorporated into the grid. We also support your operations & maintenance across its entire lifecycle. From aiding in equipment selection to implementing predictive maintenance planning, we utilize state-of-the-art digitalization tools, including advanced analytics, AI, and machine learning. The end goal is to bring significant reductions in downtime, operational expenditure (OPEX), and the LCOE.
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