EBOOK

The complexity of renewables

Twelve of PSC's subject matter experts weigh in on the complexities – and opportunities – involved in the energy transition.

Specialist Consultants
to the Electricity Industry
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Introduction

By harnessing the power of the sun, wind, water, and other natural resources, we can reduce our dependence on fossil fuels and lower our greenhouse gas emissions. However, transitioning to a renewable energy system is not as simple as flipping a switch. There are many technical challenges and complexities involved in integrating variable and distributed sources of energy into the existing grid infrastructure, as well as developing new technologies and policies to support them.

Integrating intermittent, inverter-based distributed energy resources like wind and solar PV significantly impacts power system dynamics, raising concerns about reliability and resilience. Addressing these challenges will require innovative approaches in power system modeling, operation, and control.

The increased integration of renewables can introduce voltage fluctuations in the grid, causing issues like harmonics, unbalanced loads, and power oscillations—negatively affecting power quality and transfer capacity.

These are just a few "tip-of-the-iceberg" scenarios that provide a look into the complexities of renewables within the power network. This eBook aims to provide a comprehensive and accessible overview of the technical complexities of renewable energy generation, covering topics including:

- Converter technology
- Control interaction, harmful oscillations
- Dynamic network equivalents
- Fault ride-through
- Reactive power capability requirements
- Frequency response
- Power quality, harmonics
- Transient stability
- Protection near renewable sources
- Security standards for a new energy landscape

This eBook is intended for anyone who is interested in learning more about the technical aspects of renewable energy generation, whether they are students, professionals, policymakers, or curious readers.

Our aim is to provide a deeper understanding of the technical complexities of renewable energy generation and appreciation of the opportunities and challenges that lie ahead in creating a more sustainable and resilient energy system for the future.

Contributing authors

This eBook would not be possible without the valuable contribution from the authors of the articles within this eBook who have generously shared their expertise and insights on the technical complexities of renewable energy within the power system.

Their articles have been abridged for space but links to the full articles are provided at the end of each article.

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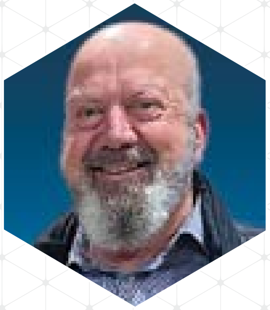

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Part 1

Converter technology

The transition toward a carbon-neutral electrical power network involves:

- Expanding renewable generation connection
- Changes in demand profile and content
- Increasing DC interconnectors use

All these aspects interface with the grid using power electronic devices, commonly referred to as converter technology. The crux of the energy transition revolves around substituting conventional synchronous generators with renewables like wind, solar, and batteries or interconnectors like HVDC. Synchronous generators store a lot of kinetic energy, which gives them strong inertia and a powerful short-circuit current; both are crucial for system operability.

Changes in demand curve

The increasing use of DERs, such as electric vehicles, serves as a practical example of a change in the demand profile and content: load profiles increase during peak charging times, and the chargers use converter/inverter technology.

Challenges with voltage control challenges

IBRs offer flexible control but have complex structures. They use fast control loops to enhance power output control (active and reactive), leading to potential instability and control problems, especially in weak grids. When IBRs replace synchronous generators, voltage regulation becomes more complicated. IBRs track grid voltage using a PLL mechanism, which can be unstable in weak grids. Analyzing PLL behavior is difficult, as root-mean-square dynamic simulation may not fully capture their behavior.

Complexities of frequency stability

Insufficient inertia causes a higher RoCoF. In Ireland, managing RoCoF protection relays due to major infeed losses was crucial; the resolution involved revising the settings. Also, delayed response in power recovery leads to concern, as controllers must supply reactive current for voltage support. Negative damping in specific electronic controls can trigger sub-synchronous resonance, amplifying currents and introducing SSCIs.

Increases in volatility

Renewables exhibit volatility due to their intermittent nature, meeting demand intermittently rather than continuously. Despite ongoing advancements in storage technology, unraveling this volatility remains a challenge.

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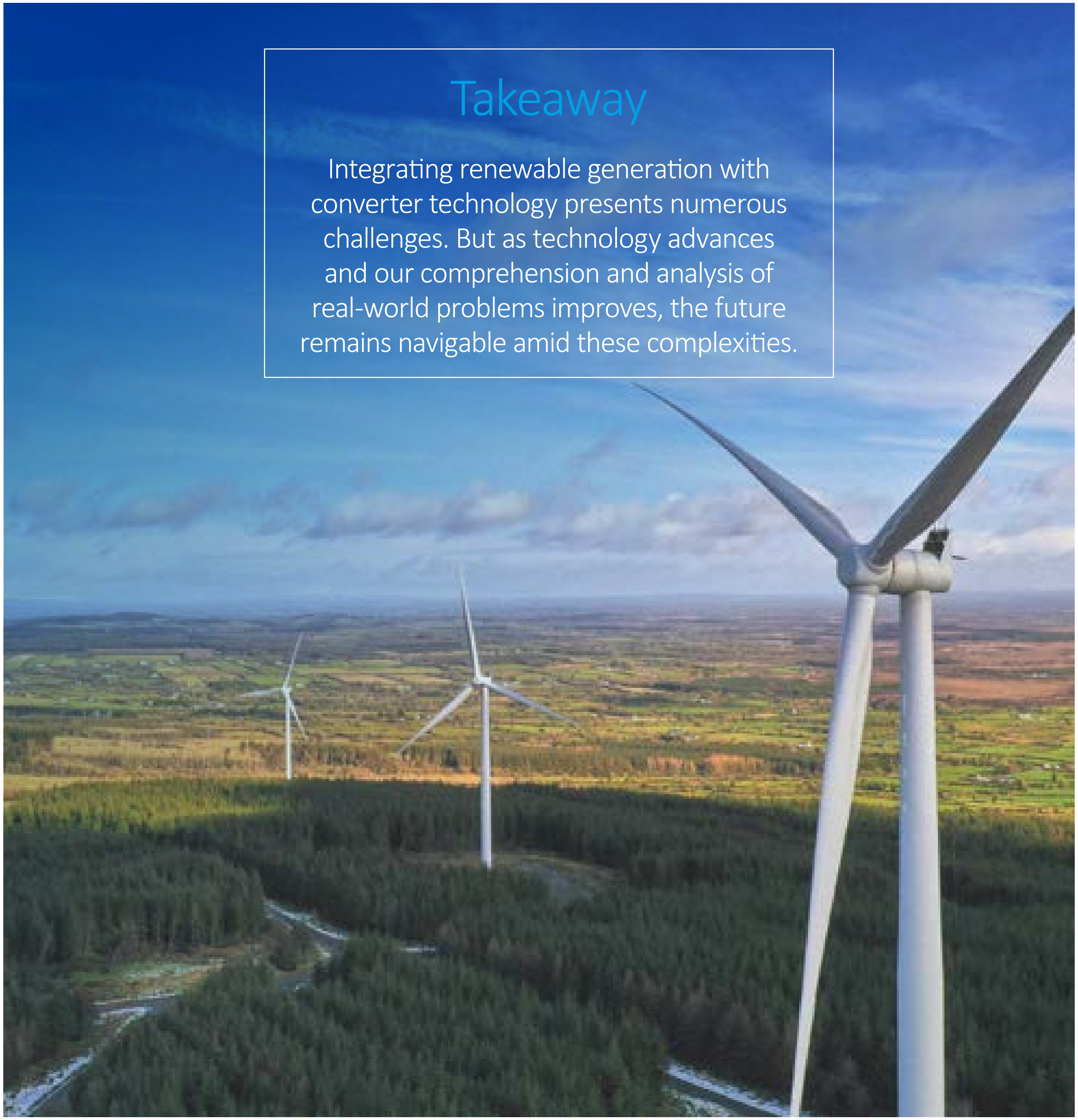

Takeaway

Integrating renewable generation with converter technology presents numerous challenges. But as technology advances and our comprehension and analysis of real-world problems improves, the future remains navigable amid these complexities.

Part 2

Control interaction – harmful oscillations

Renewable energy growth, demand changes, increased power electronics, series capacitors, and more HVDC links alter network operations, causing complexity through harmful interactions with network-connected power electric devices. Previously termed SSO, these challenges involve significant energy exchange with turbine generators after disturbances, at frequencies below the system's synchronous frequency. The 1970 series capacitor compensation incident at the Mohave Generating Station in Southern Nevada sparked major research and development on three generator-system interactions: induction generator effect, torsional interaction, and torque amplification (transient torque effect).

Device-dependent oscillation

SSOs are fast-power regulation devices that include power system stabilizers, HVDC converter controls, SVCs, high-speed governor controls, and variable speed drives. SSTIs are subject to sub-synchronous control instability, which has no mechanical interaction or fixed frequency of concern. Unintended behavior and interaction among power electronic system controllers (e.g., SVCs, STATCOM, UPFC) also pose risks, occurring between HVDC converters and FACTS devices.

Oscillations types

The focus is typically on three types of oscillations: electromechanical (0–3 Hz), small-signal or control (2–15 Hz), or harmonic resonance analysis (> 15 Hz). Interactions can occur when control systems trigger sympathetic responses between HVDC converters in different DC links. For instance, a minor disturbance in one link can lead to a corresponding reaction in another through line current commutation.

Analysis techniques

Minimizing harmful oscillation risks during system planning has prompted three analysis techniques: frequency scanning, eigenvalue analysis (modal analysis), and time domain analysis. Nyquist stability analysis is also used for impedance-based examination of SSO between wind farms and HVDC systems.

Mitigating oscillation

Each interaction is unique, with specific parameters, network topology, triggers, and results. One solution can't cover all interaction scenarios, and designing control systems to account for all possibilities is impractical. Using advanced analytical tools like real-time digital simulators and advanced communication protocols during system planning, asset acquisition, and implementation can help minimize external interference.

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Takeaway

Interactions among power electronic-driven equipment and unintended control responses to external events are possible. Structured analysis approaches and processes are in development. When identified, various mitigation strategies can be implemented.

Currently, real-time simulation helps us understand and identify possible interactions or operational problems by modeling different scenarios and controls. As the energy transition progresses, we can expect such technical complexities and should view them as manageable hurdles, not insurmountable roadblocks.

Part 3

Dynamic network equivalents

Adding renewable energy sources to power systems has become a priority. Researchers use detailed simulations (e.g., RMS, EMT) to study their impact on the grid, but this can be complex and time-consuming. The dynamic network equivalents approach streamlines grid models, maintaining accuracy while accelerating simulations. Network equivalents downsize the original electrical system, facilitating focused analysis. They retain system behavior for specific studies, adding complexity as needed. Network equivalents vary in complexity depending on the study type, providing a balance between detail and simplicity for steady-state and dynamic simulations like electromagnetic transients or transient stability.

Meeting various needs

For instance, using network equivalents is most appropriate due to tool limitations in certain EMT-type programs like PSCAD studies. They also enable real-time simulation for control device tests (e.g., FATs) in platforms like RTDS and OPAL-RT.

Creating a network equivalent

Creating a network equivalent can reduce computation times or is valuable when you do not have information about the original network. Selecting the appropriate network equivalent representation will depend on the analyses required and can create complexity on the reduced network. For example, a steady-state analysis is less complex than a dynamic analysis. Creating a network equivalent involves partitioning the original network into three parts: retained subsystem, reduced subsystem, and retained coupling lines between both subsystems.

Various modeling and methods

Classic modeling methods include the Ward Equivalent and REI: Ward uses linear admittances between retained nodes, with nonlinear parts for generation and load. REI groups nodes, creating common nodes; there can be separate REI nodes for load and generation.

Validating and implementing network equivalents

Validating the accuracy of the derived network equivalent requires test event simulations that are compared in both the original and simplified networks.

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Takeaway

Implementing network equivalents presents a challenge in capturing the network's dynamic response because it involves grouping generators with similar post-disturbance behavior and adapting controllers to match the original system. For real-time simulators, there may be limitations in terms of network size, unlike typical dynamic network equivalents used in power system studies. Additional challenges may arise due to constraints in element component definitions, such as negative loads and transmission line time constants.

Part 4

Fault ride-through

Electricity networks are becoming complex due to renewables like wind and PV using IBRs, which impact dynamic response and predictability. Beyond electricity generation, various technologies and infrastructure ensure transmission and distribution, with occasional faults expected. Network resilience is vital to handle faults and supply-demand fluctuations; FRT is a mitigation strategy.

FRT is crucial for modern grids

Fault ride-through helps generators withstand and recover from short-term disturbances like voltage sags due to network faults. FRT is essential for electric network stability and reliability, especially with more renewable energy sources, which can affect grid frequency and voltage stability. Maintaining connections and supporting power injection during disturbances can prevent network instability.

Grid codes define FRT requirements for generators

Grid codes ensure a secure and reliable power supply; they specify generators and HVDC connectors grid connections, including FRT behavior. Compliance is essential and subject to evolving power system needs. Grid codes define fault voltage levels for generators to avoid total voltage collapse and are updated as system requirements and network characteristics evolve. Ensuring generators inject reactive power for recovery, verified through studies, enhances network stability and warrants evaluation.

Synchronous generators bolster the grid

The inertia and natural response of synchronous generators stabilize voltage sags by adjusting rotor angles and injecting substantial current. High-quality excitation systems and power electronics ensure a robust response to grid changes post-fault. Design improvements for FRT include low-resistance, high-fault current-capable windings, protective devices, and power electronics for current control.

Wind turbines and FRT grid codes

Wind turbines must meet grid code FRT requirements to prevent damage during low-voltage events. They use power electronics for control, typically as fully converter-connected or doubly fed induction generators with partial power back-to-back converters that regulate rotor speed and power to the grid. Despite the inertia from rotating blades, power electronics decouple the generator from the network, diminishing the system's kinetic energy benefits.

IBRs can complicate converter controls

Unlike synchronous generators, IBRs delay fault current injection by ~10–20ms at 1.2x the rated current. IBRs can configure power output based on converter control design and protect switching devices from excessive currents during faults. Precise simulation requires detailed inverter models and a control strategy. As IBRs become more common, electromagnetic transient studies and RMS simulations will be essential for accurately modeling their behavior and device interactions.

Takeaway

FRT is vital to power system design and operation. Various techniques and technologies are available to ensure that power systems can withstand and recover from fault events.

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Part 5

Reactive power capability requirements

Reactive power capability in electrical grids is crucial for stable voltage and efficient energy transmission. Let's explore the fundamentals and uncover why they're vital for a reliable electricity supply.

Regulatory codes

Reactive power in electrical networks is either generated via capacitive cables or absorbed via transformers. Synchronous generators can generate or absorb reactive power based on excitation. A plant's reactive power capability is assessed at the POI, where power is delivered to the network system. Regulatory codes mandate a plant's reactive power capability to maintain voltage within specified ranges and conditions.

Analysis inputs and expected outcomes

Several essential inputs are required to conduct a reactive power capability analysis for a plant:

- Reactive power capability requirements, specified by the relevant code and based on connection voltage levels (distribution or transmission)
- Electrical plant model, encompassing all network components and typically created in DIgSILENT PowerFactory simulation software
- P-Q capability curve, derived from manufacturer data sheets and defined by its MW and MVAR operating characteristics

The study evaluates if a system meets the requirements; it includes load flow assessments without external reactive compensation, covering a wide voltage range (0.95–1.05 pu) and power factor variations at the POI. Results determine compliance. If not met, external compensation options like variable shunt reactors, SVCs, STATCOMs should be considered.

When to consider external compensation

Site studies determine the acceptable levels for external reactive power capacity. Operators use the data to determine if there is a need for external sources and determine needed equipment. Generation plants can increase their reactive power capacity and meet interconnection requirements with support equipment like SVCs and STATCOMs. Steady-state and quasi-static analysis methods also determine external compensation needs. Synchronous generators often comply without it, while inverter-based resources typically need it to meet relevant codes.

The role of BESS in modern electric grids

BESS ensure stability by supplying reactive power when charging and discharging. Failure in this role can cause grid disruptions and blackouts. BESS manages reactive power during regular operation and under fault conditions. However, balancing this with active power requires larger inverters, which may lead to high transformer loads and BESS overheating during prolonged high reactive power use. Smaller domestic BESS installations typically lack reactive power support but may provide it in aggregation schemes for ancillary services.

Providing flexible network support

A plant’s reactive power capacity can provide flexible network support and improve efficiency. However, adopting it for low-carbon technologies requires new services and optimizations for faster integration. Modern grid-forming inverters in DERs can adjust their reactive power, affecting POI voltage. DERs can provide necessary reactive power when enabled, eliminating the need for distribution capacitor banks or reactors.

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Takeaway

Generation plants must adhere to minimum reactive power capability standards when connecting to T&D networks. As DER penetration rises, utilities must address fluctuating voltage profiles. Leveraging reactive power capability to deliver localized voltage support can encourage DERs to offer grid services efficiently.

Part 6

Frequency response

In an electricity network, balancing power generation with customer demand is crucial. Imbalances can harm equipment, trip systems, and cause blackouts, affecting the network infrastructure. Network operators manage imbalances by instructing plants to adjust their demand or generation. For frequency response, automatic systems are activated promptly to maintain the required frequency.

The three levels of frequency control

Each frequency control level (primary, secondary, and tertiary) has a different response time after a significant generation loss. During initial recovery, synchronous generators and inverter-based resources (IBRs) boost power output. The energy system operator oversees post-recovery management from all three levels, while network operators ensure frequency remains stable at the primary and secondary levels. In some markets, these roles are combined into one entity.

The case for inverter-based resources

Increasing IBR connections in the network reduces stored kinetic energy, impacting stability, causing significant frequency deviations, triggering under-frequency load shedding—resulting in customer disconnections. Rapid frequency changes can accidentally shut down embedded generators and cause a chain of more shutdowns. Fast-acting IBRs provide frequency response solutions, while grid-forming inverters offer better voltage and frequency control independently from the grid signal.

The need for simulation studies and site tests

Simulation studies using a plant-specific model are done during detailed design with power system analysis software. They check if the controller and system response meet regulatory codes. Commissioning involves site tests to ensure compliance with code requirements comparing them to simulation results to validate plant models. The validated models are submitted to the network operator for additional studies.

The structure of frequency response tests

Frequency response tests, defined in relevant regulatory codes, usually involve simulating frequency deviations in the governor and load control systems. These tests assess how the systems react to different conditions, like varying load points and frequency signals with specific ramp rates. They also check how well the systems respond to sudden frequency changes.

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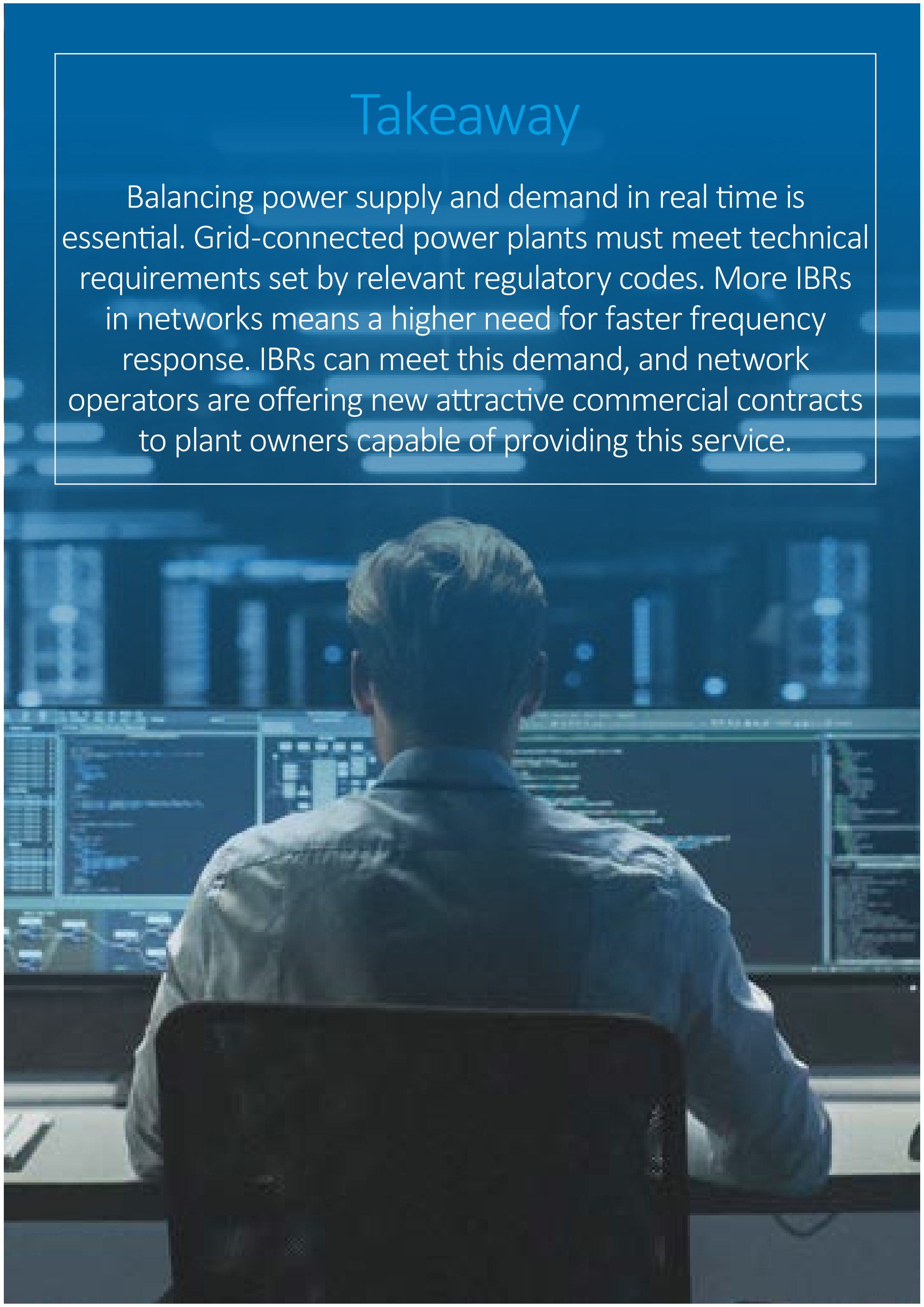

Takeaway

Balancing power supply and demand in real time is essential. Grid-connected power plants must meet technical requirements set by relevant regulatory codes. More IBRs in networks means a higher need for faster frequency response. IBRs can meet this demand, and network operators are offering new attractive commercial contracts to plant owners capable of providing this service.

Part 7

Power quality – harmonics

Power quality is how well a power supply matches established criteria for voltage, frequency, and waveform. It includes harmonic distortion, unbalance, and voltage dips. IBRs use a lot of power electronics, which can produce harmonics (e.g., 100 Hz for the 2nd harmonic if the frequency is 50 Hz).

The issue with harmonics in power systems

First, during events like transformer energization, inrush currents can briefly spike voltage to potentially harmful levels. Second, power electronic devices and nonlinear loads can emit ongoing harmonics, causing voltage drops and distortion for others based on system impedance. Introducing high-capacitance elements like long HVAC cables can change impedance characteristics and alter existing harmonics.

The side effects of harmonics

Permanent harmonic distortion in the system poses challenges. Mainly, it generates excess energy, causing heating in various cables, transformers, and capacitor banks. Additionally, harmonics are detrimental to protection devices and high-accuracy meters, potentially leading to maloperation.

Managing harmonics levels

Utilities conduct intricate studies to determine the allowable level of harmonic distortion from a customer seeking connection. These studies set emission limits using comprehensive modeling and analysis and share system impedance characteristics with the customer. Typically depicted as impedance loci, these characteristics often encompass harmonic ranges due to modeling uncertainties. Wind or solar developers use this data to evaluate their project's impact on the connection. Exceeding emission limits can create compliance issues or breaches.

Mitigation measures to prove compliance

Common mitigation includes using passive shunt harmonic filters: single-tuned, double-tuned, high-pass, or C-type. These filters create a low-impedance path for specific frequencies, altering the system's response. Their design involves reassessment studies to ensure compliance under all conditions. In many European countries, a desktop analysis report is submitted to the utility to show a customer's compliance. Verification usually occurs during commissioning where measurements are taken at the connection point before and after energization. Continuous monitoring may follow to track harmonic distortion trends and system changes.

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Takeaway

Harmonics are introduced into the power system by using a high degree of power electronics in inverter-based resources. Analytical approaches assess impacts, and available mitigation measures can be successfully introduced.

Part 8

Transient stability

Power systems are complex networks that generate, transmit, and distribute electricity and ensure continuous, safe, and reliable power supply. Power system stability analysis assesses stability after disruptions. Transient stability is the system's ability to stay synchronized during severe disruptions such as short circuits or abrupt load changes. Failure in this area can lead to major disruptions and system-wide blackouts.

The need for transient stability analysis

Transient stability analysis can differentiate between small and large disturbances, analyze the system's ability to return to steady-state operation, and assess how generators react dynamically with the rest of the system. The objective is to find the maximum duration of a disturbance before losing synchronism (critical clearing), which requires mathematical models and high-speed computer simulations because of the system's dynamic and nonlinear nature.

The impact of RES on power system stability

Integrating RES into global power systems has grown over the last decade due to environmental concerns, technological advancements, economic incentives, and available resources. RES often uses CIGs to convert DC power to AC power for the grid. Unlike traditional generators, CIGs lack a physical rotating mass connected to the grid, affecting system inertia. This distinction is critical when assessing the impact of RES on power system stability, particularly transient stability.

The role of fast frequency response

Integrating RES and CIGs on a large scale presents unique challenges for power system transient stability analysis. To counter low inertia issues, FFR is often used to inject power quickly into the grid during frequency deviations. A study shows FFR can stabilize frequency but may reduce transient stability, especially near critical generators in "weak systems" with limited conventional generation. Designing FFR schemes requires a comprehensive approach, considering frequency response and intricate factors that are unique to each power system under analysis, affecting transient stability, particularly in systems with substantial renewable generation.

Integrating RES and CIGs into power systems

The rapid transition towards integrating RES and CIGs in power systems presents opportunities and challenges. Low-inertia systems are more prevalent, and transient stability remains crucial, with faster dynamic responses. Implementing FFR to control frequency deviations requires careful planning to avoid unexpected reduction in transient stability, especially near critical synchronous generators. Traditional methods tailored for synchronous generators may struggle with CIG and RES dynamics. But developing new tools and methodologies for these systems is a major challenge for

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Takeaway

As power system change, transient stability analysis methods also need to evolve. Increased grid heterogeneity, decentralization, and the need for real-time or near-real-time stability analysis present new and complex problems that require innovative solutions.

Ongoing research is essential to understand the complexities and develop methodologies that ensure power systems continue to be reliable and stable.

Navigating transient stability complexities, in the era of renewable energy and low-inertia systems, is possible with careful, ongoing research and continuous innovation, steering toward a sustainable future.

Part 9

Protection near renewable sources

Traditionally, power networks relied on big generators fuelled by coal, gas, or nuclear power. Nowadays, we're shifting to cleaner, sustainable energy sources like solar, wind, and batteries. The large synchronous generators had strong fault currents due to their inertia, helping protection engineers distinguish faults from normal currents. Newer asynchronous inverter-based resources (IBRs) behave unpredictably during faults due to varied controller designs and physical properties; they usually produce ~1.2x their rated current during a fault, making it harder to identify faults. This event triggers further issues in the network, such as difficulty for the IBRs with PLL controls to track properly the voltage waveform, which ultimately may provoke the undesired disconnection of large amounts of more IBRs.

The issue with protection near renewable sources

Protection engineers need innovative methods to distinguish faults from regular loads. Some suggest maintaining high fault currents with synchronous condensers for better protection detection, but this can stress electrical equipment. Conversely, lower fault currents are less damaging to equipment. Protection should be inactive during regular conditions, often for many years. When activated, it should be reliable (operate when required), selective (isolate only faulty sections, minimize disruption to healthy circuits), and stable (unaffected by conditions external to protected zones).

The difference between the common fault detection techniques

Three main techniques are widely used in fault detection: overcurrent, impedance, and differential. Overcurrent occurs when a fault causes a current increase. Impedance measures the change in voltage and current during a fault. Differential monitors the balance between current entering and leaving a circuit under normal conditions, but this balance is disturbed during a fault.

Reducing fault levels creates overcurrent detection issues

Impedance protection has been shown to be unreliable near inverter-based sources due to the fault characteristics and sequences components. In these cases, distance relays aren't advised; IBRs do not produce reliable negative sequence currents. Research indicates that IBRs could provide reliable negative sequence current, but more study is needed. Fortunately, current differential protection is reliable, as it compares input and output currents to detect faults.

Manufacturers and researchers support safeguarding renewable sources

Protection manufacturers and researchers publish a lot on safeguarding renewable sources. Some are suggesting new distance protection algorithms and alternative techniques. A significant advancement is using traveling waves to detect faults, reducing reliance on fault current strength. First used in fault locators, this method is now accessible through commercial relays, precisely pinpointing fault locations using electromagnetic waves from faults.

System protection or remedial action schedules don't detect faults

System protection or remedial action schemes don't detect faults directly. Instead, they're configured to detect predetermined system conditions, often based on studies. They act proactively and sustain system stability, managing voltage and frequency. This involves modifying or shutting down generation, adjusting loads, or reconfiguring the system.

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Takeaway

As renewable energy grows, concerns about system inertia and fault levels dropping were anticipated for the future. Yet, inverter-based generation has already led to notably low fault levels in certain networks. These challenges have transitioned from future predictions to present-day realities.

Part 10

Security Standards for a New Energy Landscape

The non-dispatchable nature of renewable resources in power systems leads to an inherent need for storage. But how do we ensure that the security standards we use with grid-connected storage solutions are fit for purpose? While a storage system in charging mode appears to the network as a load, the social and economic consequences of an interruption to its connection differ from those caused by an interruption to consumer loads.

For this reason, one logical solution is for storage connections to be treated as a separate section of any security standard. In addition, the definition of load groups for load security should not include storage systems when they are in charging mode.

The dual role of storage systems

We already know that the intermittent nature of renewable generation means that significant volumes of energy storage are necessary for the correct functioning of the network. When exporting, this appears to the network as non-synchronous generation (NSG), with all the consequent considerations of infeed loss risk for frequency response. However, storage would appear on the network when charging as a load.

Consequences of loss of load

In a conventional AC power system, the consequence of the loss of a load following a fault is a rise in frequency. In future grids – which may be dominated by power electronics – the consequences will depend on the control configuration of converters and other devices.

If the power imbalance in the local network is transferred to a remote interconnected AC network – either by using a common frequency reference for all inverter-generated grids or other means – then a loss of load will lead to a rise in frequency. However, if the local frequency is maintained regardless of the power imbalance, the consequence will be a rise in voltage.

In either case, the network must be designed so that an appropriate response and reserve are in place to contain the consequence within acceptable limits.

Recognizing outfeed loss in security standards

As power systems continue to evolve rapidly, now would be a prudent time to define two terms that address two types of risk: Normal Outfeed Loss Risk (NOLR) and Infrequent Outfeed Loss Risk (IOLR).

The definition of a NOLR could easily be based on the frequency control response and active power reserves for frequency events. These are already required to ensure frequency levels are kept within defined values for the most probable events that disconnect loads or storage connections in their charging state.

In practice, the NOLR would correspond to the size of the largest storage facility that can be connected so that a single circuit breaker controls it. Alternatively, it could be controlled by a combination of circuit breakers opening together to clear a fault at a single point.

The IOLR would, as its name suggests, be based on less probable events that exceed the values defined for the NOLR. This would correspond, for example, to the loss of a complete storage installation at a single site.

Security standards fit for purpose

A frequency or voltage rise (depending on the detailed control logic for inverter-formed grids) will occur in response to a loss of load, whether this consists of charging storage units or end-user load. However, there are additional requirements for the end-user load to meet the load's security expectations.

These requirements would not be appropriate for energy storage facilities, where the power exchange with the network is much more likely to be managed as an operational tool by the system operator. So, the PSC recommendation is that these requirements for storage connections and end-use load should be addressed separately in different sections of the associated security standard.

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Takeaway

Ultimately, the security standards we apply should reflect the practical realities of any power system. In power systems incorporating renewable sources of generation, storage is an essential element. Security standards should reflect this by adopting NOLR and IOLR definitions that are separate from standards applied to end-use loads.

Conclusion

While renewables bring a variety of new technologies that solve problems and create efficiencies (e.g., storage and distributed energy resources), these same technologies can make systems more complex.

A successful transition to a carbon-neutral electrical power network will require a sober and in-depth assessment of the various complexities presented in this eBook and others not discussed. Creativity and a commitment to collaborative problem-solving will be a necessity to reach the projected targets.

At PSC, we believe complexity should be embraced rather than ignored. Addressing the complexities of renewables involves careful planning and using emerging technologies to build a more extensible infrastructure to support the energy transition.

Remember: Renewable energy is not only a technical challenge but also an opportunity for collaborative problem-solving. Together, we can power a sustainable world for ourselves and future generations.

Acronym list

Here's a comprehensive list of acronyms used throughout this eBook.

BESS	Battery energy storage systems
CIG	Converter-interfaced generation
DER	Distributed energy resources
EMT	Electromagnetic transient
FACTS	Flexible AC transmission system
FFR	Fast frequency response
FRT	Fault ride-through
HVAC	Heating, ventilation, and air conditioning
HVDC	High-voltage direct current
Hz	Hertz
IOLR	Infrequent Outfeed Loss Risk
IBR	Inverter-based resource
MW	Real/active power
MVAR	Reactive power
NOLR	Normal Outfeed Loss Risk
NSG	Non-synchronous generation
PLL	Phase-locked loop
POI	Point of interconnection
REI	Radial equivalent independent
RES	Renewable energy sources
RMS	Root mean square
RoCoF	Rate of change of frequency
SSCI	Sub-synchronous control interaction
SSTI	Sub-synchronous torsional interaction
SSO	Sub-synchronous oscillation
STATCOM	Static synchronous compensator
SVC	Static var compensator
T&D	Transmission and distribution
UPFC	Unified power flow controller
WTG	Wind turbine generator

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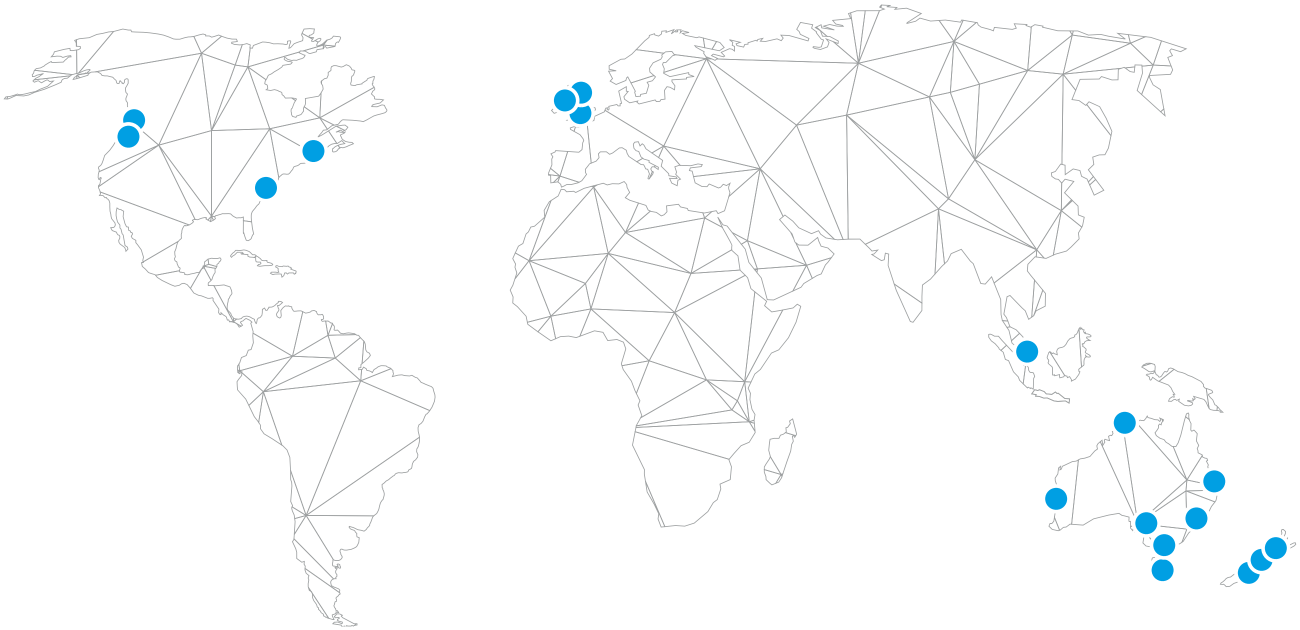

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