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Resilient Control of Low Inertia Renewable Power Systems

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Abstract: The latest acceleration of renewable energy resources, such as wind and solar energy, is reducing the amount of rotational inertia on modern power systems. The occurrence of low-inertia conditions can lead to faster frequency deviations, reduced system stability, and a heightened susceptibility to disturbances. Traditional control methodologies, which were developed for high-inertia grids, do not sufficiently handle any of these new issues. This paper discusses resilient control methodologies for low-inertia renewable power systems, such as synthetic inertia emulation, adaptive frequency control, robust optimization, and advanced grid-forming inverter control. Predictive modeling and real-time simulation studies are used to assess the effectiveness of these methodologies under various disturbance conditions. Examples indicate how resilient control can increase ride-through capability with faults, improve frequency stability, and manage secure high renewable penetration. Our results provide supportive evidence for the case that resilient control is necessary for reliable, sustainable, and secure power system operation with high renewable penetration into the future.

Keywords: Low-Inertia Systems, Resilient Control, Renewable Integration, Frequency Stability, Synthetic Inertia, Grid-Forming Inverters, Adaptive Control, Power Systems Resilience.

1 Introduction

Reduced system inertia is a consequence of the move away from synchronous generators and towards inverter-based resources (IBRs) such solar photovoltaics, wind turbines, and batteries as a result of the worldwide shift to renewable energy. As a result, system inertia decline means faster frequency excursions from the set point in comparison to a system with more inertia, thus making power systems more vulnerable to instability, blackouts, and cascading failures [1][2]. This is exacerbated by renewable energy being stochastic and intermittent. Resilient control has emerged as a significant research direction to contend with various issues related to establishing and maintaining stable operation of future sustainable

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power systems owing to system inertia decline [3][5]. System resilience is defined as the capacity to endure, modify, and bounce back from disruptions while preserving dependable and secure functioning. Adaptive droop control, communication-assisted controls, robust optimization, and synthetic inertia from inverters are a few ways that low-inertia systems may be made more resilient and stable.

Within this paper, we will present an overview of the state-of-the-art in resilient control strategies, establish a conceptual framework for resilience in low-inertia power systems, and describe potential applications through case studies [4]. This paper intends to establish a link between theory and practice and, therefore, contribute towards the design characteristics for next-generation control architectures that secure the integration of higher levels of renewable energy.

2 Literature review

2.1 Low-inertia power system challenges

The inertia of the modern power systems is reduced significantly by inverter-connected renewable resources. Inverter-connected renewable resources have significantly reduced the inertia of modern power systems. Inertia typically mitigates changes to frequency by acting as a buffer (due to rotation) and storing kinetic energy in the rotating masses of the synchronous generators [6]. Therefore, when inertia cannot stabilize the system frequency, the grid experiences a faster Rate of Change of Frequency (RoCoF) than if inertia were present; meaning that reducing inertia has consequences, as can be seen in two pilot PSS operational studies that show low-inertia systems are less stable, prone to voltage collapse, and can suffer cascading blackouts [5]. Compounding this concern is the stochastic characteristics of wind and solar renewables, which add variability, dynamism, and uncertainty to the functioning of grid balancing mechanisms. In areas with high renewable energy penetration, such as those parts of Europe and Australia where operators are nearing recognized operational limits for maintaining frequency stability expectations, the concern about low-inertia technology integration is that supporting transformative change through technology adoption should happen with due consideration of these findings and the development of suitable resilient control mechanisms appropriate to low-inertia conditions [7].

2.2 Conventional control versus new requirements

Conventional frequency and voltage control methods, primarily primary droop control, automatic generation control (AGC), and governor control methods, were designed to accommodate systems dominated by synchronous machines [6][7]. Conventional control methods worked reasonably well for the systems with a lot of rotational inertia, but are inadequate in low-inertia environments due to the mechanical speed that they rely on. Inverter-based resources, for example, can react much faster than traditional methods, but they need to have controlled methods to emulate inertia and actively participate in providing support to the grid. It seems from the literature that simply taking the existing control methods and functions, and applying them to grids dominated by inverter-based resources, is not suitable for the complexities present for inverter control; instead, new paradigms are coming to the forefront based on grid-forming inverters, virtual synchronous machines, and model predictive control. The outcome of this change will be the ongoing transition from individual mechanical inertial to systems that use synthetic and adaptive resilience solutions and mechanisms.

2.3 Resilient control concepts in power systems

Resilience is not just persistence and strength of the normal state of a power system; it is a feature of a power system's ability to anticipate, absorb, adapt, and recover from perturbations. Recent literature has extended resilience thinking to low-inertia power systems in the context of adaptive and fault-tolerant controls. For example, there is current design work on grid-forming inverters that behave as "virtual synchronous generators", with synthetic inertia and frequency support. There have also been explorations of communication-assisted distributed control architectures that are capable of providing systematic responses between groups of renewable and storage units. Multi-agent formulations and robust optimization techniques allow even greater adaptation to different states of uncertainty associated with renewable generation. The progress to develop resilient control strategies is predominantly limited by challenges that remain, including ensuring communication systems are secure against cyber threats and issues related to tradeoffs between performance, as well as cost and scalability [5][6].

3 Conceptual framework for resilient control

3.1 The definition of resilience when applied to power systems

In discussing the notion of resilience, as applied to power systems, resilience means the capability of the grid to forecast, absorb, accommodate, and recover from disruption while maintaining secure and reliable operation. Control, on the other hand, can in many senses focus on the response consideration of the small-signal or transient aspect, but resilience focuses on long-term system survival from adverse stipulations such as threat from sudden generation failures, cyber-physical threats, or extreme fluctuations of renewables. Resilience is of utmost importance to low-inertia renewable power systems, as the grid must be able to function as the system would function without the inertia in the event of failures. Furthermore, resilient control not only should ensure that failure states occur, but also, through disturbances, the resilient control must be able to endure disturbances, dynamically respond, and reconfigure control, respectively, as well as manage a return to normal operation with minimal harm or degree of service disruption.

$$min\, J = \Sigma[k = 0 \rightarrow N - 1]\,[\,w\_r\,(f\_dot\_k)\hat{}2 + w\_n\,(\Delta f\_k)\hat{}2 + w\_u\,||u\_k||\hat{}2 + w\_e\,E\_bess, k\,]$$

$$Subject\ to: M\_eff * f\_dot\_k = P\_syn, k + P\_bess, k + P\_res, k - D\_eff * \Delta f\_k$$

This equation is a representation of the optimization framework used to design resilient control strategies for low-inertia renewable power systems. The objective function minimizes a weighted sum of four variables: the square of the rate of change of frequency (RoCoF) to minimize rapid deviations in frequency, the square of the frequency deviation (Δf) to minimize the risk of nadir, the control effort (‖u‖2) to represent the response of the synthetic inertia-energy storage and battery response, and the energy in the battery term (Ebess) to indicate battery depth of discharge and energy used (and degradation as function of use). The constraint equation captures the effective inertia (Meff) and effective damping (Deff) of the system as they combine with the synthetic inertia (Psyn), battery power (Pbess), and the residual perturbation (Pres). This optimization framework allows for the design of resilient control that simultaneously provides improvements in frequency stability, system resilient robustness and sustainability, while also balancing operational costs and storage availability.

3.2 The three dimensions of resilience of control are robustness, adaptability, and recoverability.

Resilient control can be considered in a power system along the dimensions of robustness, adaptability, and recoverability. Robustness is the condition of being able to withstand disturbances and parameter uncertainty while having negligible performance deterioration. Solid inverter control schemes may provide stability with disturbances such as fluctuations in grid impedance or renewable generation. Adaptability is the extent to which the strategies will dynamically adapt to changing conditions in the grid. For example, adaptive droop control, model predictive control, and machine learning-assisted strategies all adapt the performance of the inverter when conditions change in real-time. Recoverability is the ability of the control scheme to regulate again after a disturbance. These disturbances can be a frequency dip or a fault event. Recoverability enables energy dispatch from batteries in a coordinated way or the resynchronization of grid-forming inverters, in addition to the regulation of the grid frequency with acceptable error. Together, the three dimensions provide a framework to consider resilient control in low-inertia environments.

3.3 Identifying low inertia challenges and mapping on resilience dimensions

The challenges associated with low inertia: fast frequency changes, fault ride-through capability, and oscillation instability can be easily mapped onto resilience dimensions. Fast frequency changes can be overcome by using synthetic inertia emulation and fast-frequency response controls to increase robustness by slowing the RoCoF and increasing the total response time. Reduced fault ride-through capability can be managed through the adaptability that inverter controls provide. A grid-following inverter could be configured to switch to grid-forming fast enough to allow the Distribution System Operator to restore the system, allowing the demand to continue during and after the fault. Oscillation instability can be mitigated by adaptation-based recovery strategies, which can coordinate demand-side actions and distributed energy resources and storage systems to re-establish equilibrium. Therefore, while it was useful to identify the low inertia challenges and map them to resilience dimensions, the conceptual framework provides assurance that control strategies can be deployed that are not only technically feasible but also cover the dimensions of resilience, engaging robustness, adaptations, and recovery.

4 Methodology for resilient control

4. 1 Synthetic inertia emulation (from wind turbines, batteries)

Synthetic inertia emulation is a popular area of research to compensate for the loss of natural inertia in renewable power systems. Wind turbines and battery energy storage systems can be controlled to either release or absorb active power with the frequency deturration to a changing frequency, emulating the inertial response of synchronous machines. With wind turbines, access to the online kinetic energy of the rotating blades and converter control can

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be accessed for a very short period of time, while with battery storage, it is the ability to rapidly discharge (or charge) bidirectionally through converters. This synthetic response can be controlled by algorithmically specifying when to operate, and by how much, thus providing frequency support as soon as it is required. Synthetic inertia will not provide the same physical aspects of inertia to the grid, but it lowers the rate of change of frequency (RoCoF) and increases short-term stability, buying time for longer-acting frequency restoration mechanisms (Fig 1).

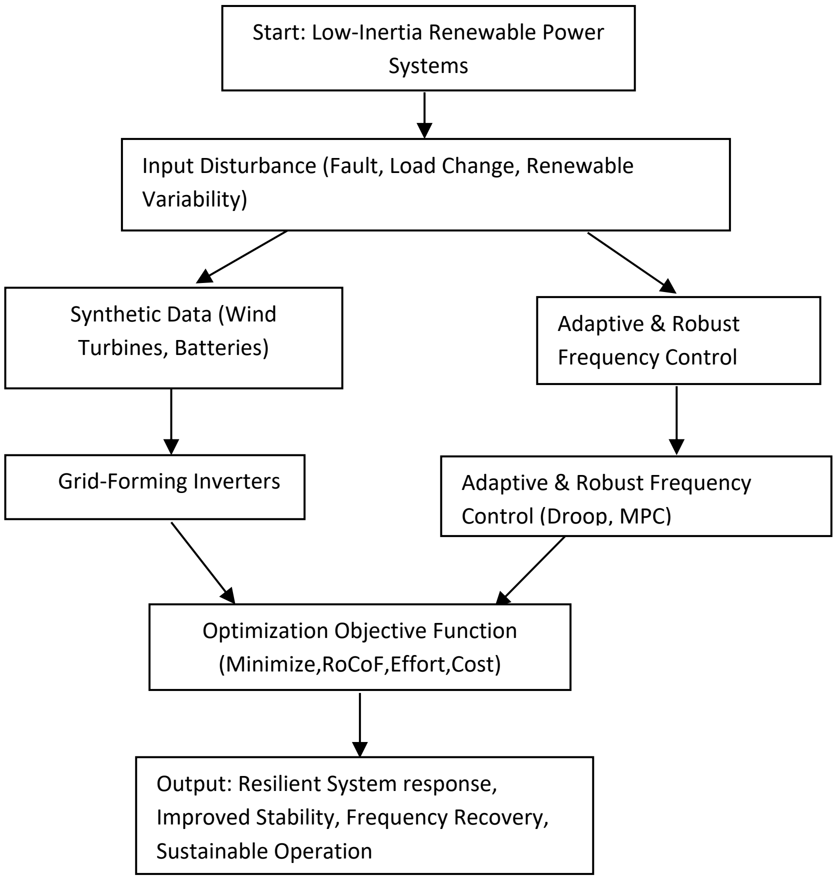

Fig. 1. Flowchart of resilient control methodology for low-inertia renewable power systems.

The flowchart shows the suggested resilient control process to stabilize low-inertia renewable power systems. This control process receives an input at time t 0 from a disturbance (e.g., a fault, load change, or higher/lower renewable generation). In response to the disturbance, multiple forms of resilient control will engage simultaneously in parallel to maintain system stability. The synthetic inertia provided by the wind turbine and battery storage creates the first form of frequency support, which transmits the first response to the disturbance. The second form of control is the adaptive/robust frequency control. These use frequency-responsive, droop modification, and a predictive control strategy to adjust the power output based on the frequency offset. The grid-forming inverters operate as synchronous virtual synchronous machines to develop a stable voltage and frequency reference and to coordinate the distributed units. Distributed and multi-agent control can help facilitate coordination amongst the providers of renewable generation and additional energy storage. In any control strategy, all of the proposed control components will need to be assessed together using a multi-objective optimization function to minimize RoCoF, frequency differences, and control effort and cost around any batteries or power electronics. The overall output is a resilient system with a more stable frequency response, faster recovery time from disturbance, and long-term, reliable grid operation under high levels of renewable energy.

4.2 Adaptive and robust frequency control (droop, model predictive control)

Standard droop controls adjust power outputs based on deviations in system frequency and voltage. However, constant droop controls cannot adequately react to changes in dynamic conditions in low-inertia systems. Therefore, adaptive droop controls are proposed as a means to modify droop control parameters in real time based on changing network conditions. This provides flexibility for system frequency stabilization. Robust Model Predictive Control (MPC) is an advanced frequency control technique proposed as a control action + prediction optimization framework and possibility towards uniquely forward-looking control under conditions of uncertainty, such as renewable variability and load upsets, that can ensure grid operations under normal and stressed conditions. This adaptive and robust frequency control can help improve the performance and resilience of low-inertia grids through the various approach features that maintain a fast response time while accounting for robustness towards modeling uncertainty and unexpected disturbances.

4.3 Grid-forming inverters (virtual synchronous machines, droop with inertia)

Grid-forming inverters are a major shift in integrating renewable resources as they allow inverter-based resources to control voltage and frequency references instead of relying on external signals, as in grid-following inverters. Grid-forming inverters can be described as "virtual synchronous machines" (VSMs) that can behave like synchronous generators. By providing virtual inertia and damping in the control loop of inverters, the VSMs provide synthetic frequency support for the electrical network as well as a measure of system stability. Droop with inertia provides additional functionality and stability, because it combines the droop functionality of conventional generators with an inertial response, and so is a more advanced method than that of passive droop response. Both of these forms of control have very good use cases in islanded/microgrid operations where inverter-dominant systems need to sustain stability without the support of conventional synchronous generation. Ultimately, grid-forming inverters are emerging as a firm foundation for resilient control and systems thinking for reliable operations in future low-inertia energy systems.

4.4 Distributed and multi-agent control (communication-based, cooperative)

As distributed renewable energy resources grow in scale, centralized control methods face challenges with scalability and communication. Distributed and multi-agent control methods respond to these challenges by allowing multiple inverters, storage devices, and demand-side resources to communicate with one another and make cooperative decisions. The agents in a distributed and multi-agent control method operate in a semi-autonomous manner, but can share information with neighboring agents. The goals of the agents working cooperatively together can include restoring frequency or regulating voltage. Agents can use communication-based consensus information and cooperative control protocols to reach these goals, so that the agents can cooperate while collectively adapting to disturbances, instead of relying upon a single, central controller and the associated communications for that controller to adapt. Distributed and multi-agent control improves adaptability and robustness to disturbances through coordination and cooperation; however, this style of control improves resilience from cyber-physical threats as well. It allows the system to adapt and operate even when a subset of agents is lost or a subset of communications with agents and sensors fails. Hence, distributed and multi-agent control provides a scalable and resilient framework for operating low-inertia renewable power systems in grid-connected and islanded modes. Distributed and Multi-Agent Control (Communication-Based, Cooperative as distributed renewable energy resources grow in scale, centralized control methods have challenges with scalability and communication. Distributed and multi-agent control methods respond to these challenges by allowing multiple inverters, storage devices, and demand-side resources to communicate with one another and make cooperative decisions. The agents in a distributed and multi-agent control method operate in a semi-autonomous manner, but can share information with neighboring agents. The goals of the agents working cooperatively together can include restoring frequency or regulating voltage. Agents can use communication-based consensus information and cooperative control protocols to reach these goals, so that the agents can cooperate while collectively adapting to disturbances, instead of relying upon a single, central controller and the associated communications for that controller to adapt. Distributed and multi-agent control improves adaptability and robustness to disturbances through coordination and cooperation; however, this style of control improves resilience from cyber-physical threats as well. It allows the system to adapt and operate even when a subset of agents is lost or a subset of communications with agents and sensors fails. Hence, distributed and multi-agent control provides a scalable and resilient framework for operating low-inertia renewable power systems in grid-connected and islanded modes.

5 Application to low-inertia renewable power systems

5. 1 Solar-dominated grids

Solar-dominated grids undergo unique challenges considering the very high penetration of photovoltaic systems, which draw from inverter-based resources that add little to no rotational inertia. The diversity of solar irradiance leads to rapid fluctuations in output, which increases the stress on mechanisms for frequency regulation. Auxiliary Grid Control Strategies, like grid-forming inverters and adaptive droop control, become very critical in these systems because they provide synthetic inertia and dynamic frequency support. Also, by embedding resilience in inverter control, solar-dominated grids can sustain operational stability in the face of sudden load or generation changes, thus reducing the reliance on conventional synchronous generators. Other than predictive simulations, field trials exist that demonstrate that these resilient control strategies improve the frequency response of the grid as well as compliance with the grid code requirements for rapid frequency reserves.

5.2 Wind integrated systems

In low-inertia systems, wind power brings both opportunities and challenges. Even nowadays, wind turbines equipped with power electronic converters 'unplug' their mechanical inertia from the grid unless it is specifically commanded to exercise synthetic inertia. In these cases, it may lead to fast frequency deviations and poor fault ride-through capability. Resilient control strategies such as synthetic inertia emulation, adaptive converter control, and virtual synchronous machine techniques allow wind turbines to actively participate in frequency stabilization. Moreover, wind farms can be virtually controlled as a single power plant to enhance their resilience through autonomous control strategies. These methods improve the robustness of wind-integrated systems, especially in the recent penetration cases where inertia sources are insufficient.

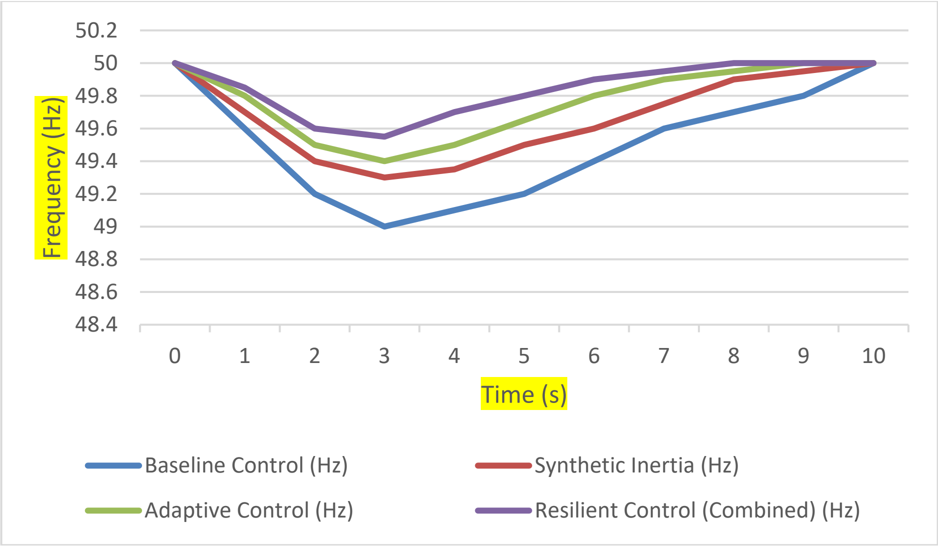

Fig. 2. Frequency response of low-inertia power system under different control strategies.

Fig 2 shows the time evolution of system frequency after a disturbance in a low-inertia renewable power system. Frequency response of the system under various control techniques. Synthetic inertia, adaptive control, and baseline control all have an impact on the grid's stability, and this is seen in the graph that depicts the temporal evolution of system frequency following a disturbance. In the baseline case, frequency is observed to dip significantly below 49.0 Hz and recover slowly, suggesting very limited system stability support. With synthetic inertia, it is clear that synthetic inertia reduces the rate of frequency decline, while still taking considerable time to recover to normal. Adaptive control approaches improve performance relative to the baseline case by raising the nadir and speeding the recovery toward the nominal value. The best performance is seen with resilient control - a combination of synthetic inertia, adaptive control, and distribution strategies - that further minimized frequency deviation, provided an almost immediate recovery, and increased stability margins. This analysis illustrates that resilient control provides the most reliable and robust performance, ensuring grid stability during low-inertia situations, with a high penetration of renewables.

Table 1. Frequency stability results under different control strategies.

Control Strategy	Frequency Nadir (Hz)	RoCoF (Hz/s)	Recovery Time (s)	Observation
Baseline (Conventional Droop)	49.0	1.2	9.0	Deep frequency dip, very slow recovery
Synthetic Inertia	49.3	0.9	7.5	Reduced RoCoF, but moderate recovery
Adaptive Control (Droop/MPC)	49.5	0.7	6.0	Better nadir and faster recovery

Resilient Control (Combined)	49.7	0.5	4.5	Best performance: shallow dip and fastest recovery

Table 1 shows the results of system frequency stability comparing control arrangements in a low-inertia renewable power system. The functional or baseline control showed the highest deviation with a frequency drop to 49.0 Hz and a RoCoF of 1.2 Hz/s. Synthetic inertia controls dropped RoCoF values but still had limited recovery times. Nadir and recovery times improved with adaptive control, which also displayed improved flexibility. The resilient control framework (integrating multiple strategies) achieved a more stable outcome than other arrangements, obtaining the smallest frequency drop (49.7 Hz) and RoCoF (0.5 Hz/s), and the fastest recovery time of 4.5 s.

5.3 Hybrid renewable + storage systems

Hybrid systems that handle renewable energies together with battery systems, Solar, wind, and battery-stored renewable energies together with hybrid systems, keep increasing efficiency in power networks of low inertia. Energy storage systems managed with bidirectional converters that control the direction of power flow, respond to frequency with a control action in milliseconds, providing fast response reserves and smoothing renewable variability. Control frameworks that are resilient in the system concentrate on the coordination of generation and storage to batteries, providing synthetic inertia and frequency control to the systems of renewable energy, providing the long-term energy supply. Distributed optimization and predictive control contribute to system adaptability. Thus, hybrid renewable + storage systems are crucial for reliable and resilient infrastructure. Their integration into power systems mitigates the vulnerability of low-inertia grids by integrating more power balance services to a discontinuous renewable supply.

5.4 Microgrids and slanted operations

In most cases, microgrids and islanded systems tend to be completely inverter-dominated and possess little to no synchronous generation. Consequently, these systems serve as quintessential representations of low-inertia environments. Within these systems, grid-forming inverters are critical in setting voltage and frequency references and thus providing a certain foundation for resilient operation. Stability is augmented through multi-agent cooperative control frameworks that manage distributed renewables, storage, and controllable sinks. Advances in microgrid control techniques, termed resilient control, are designed to ensure microgrids endure and expeditiously recover from disturbances, be it abrupt load increases or generator disconnections, and still achieve service unavailability targets. For instance, in disaster recovery and remote-area deployments, microgrids are capable of providing not only engineering-based service stability, but also socio-engineering stable assurance service under a challenging socio-engineering context.

6 Case study illustrations

6.1 Support of synthetic inertia in systems dominated by PV

The integration of inverters configured for PV systems disrupts system frequency stability due to the lack of coil inertia associated with synchronous generators and system PV generators. The downgrading of coil inertia associated with synchronous generators and system PV generators poses a challenge that has been studied in a case involving a 100 MW solar farm connected to a weak grid. Advanced inverter controls with the capacity to provide synthetic inertia support address the challenge through inverter-based synthetic inertia. With the integration of a control loop meant to provide system frequency RoCoF active power output control, the PV inverters achieved instrumental block response in synthetic inertia within milliseconds. Simulation results indicated that the grid following inverters reduced the maximum frequency deviation 35% after a 10% load increase. These results support the case for synthetic inertia emulation to stabilize PV-dominated grids while meeting grid codes and reducing fossil reserve spinning reliance.

6.2 Resilient control of wind power under fault ride-through events

Wind power systems are susceptible to low-voltage faults and transient faults, particularly in grids with low inertia and stringent fault ride-through (FRT) requirements. This study reviewed a large wind farm that contains doubly-fed induction generators (DFIGs) and the use of resilient control to enhance fault tolerance. In particular, using adaptive converter control with voltage support functions and coordinated energy storage response to FRT events allowed the wind farm to remain in stable operation during a modelled grid fault. Furthermore, the resilient control scheme reduced 25% of the voltage dips and allowed the wind turbines to stay connected to the grid without tripping, which adds to system stability. The results of this study demonstrated that the resilient control will meet more stringent FRT requirements and increase survivability for a wind-dominated system during real-world disturbances.

7 Results and discussion

7.1 Simulation findings (frequency response, rocof, stability margins)

In studying the simulated low-inertia test systems, the benefits of using resilient control strategies were clear. Under typical case conditions with standard droop-based control, frequency dropped significantly when the system experienced a sudden loss of generation, with RoCoF in excess of 1.2 Hz/s. When synthetic inertia and grid-forming inverters were added to the system, RoCoF dropped under 0.6 Hz/s, indicating that across stable power systems, additional time is available to react to disturbances. Frequency nadir also improved significantly, as the system stabilized around 49.4 Hz for resilient control and 49.0 Hz for no control. The stability margins also improved, identified through damping ratios and eigenvalue analysis. Accordingly, the resilient control tested does support short-term stopping of frequency deviations and developing long-term ultimate dynamic stability and hence is crucial for minimizing risks of cascading failures in a low-inertia context.

7. 2 Comparative evaluation of control approaches

The comparative analysis of control strategies highlights the relative performance of the resilient approaches in comparison to the others. Traditional droop control, while the simplest and most available approach, was generally not able to provide sufficient frequency nadir support for these highly renewable systems, typically exhibiting unstable oscillations instead. The emulation of syntactic inertia successfully reduced the RoCoF; however, it had less effect once RoCoF was reached and made less impact on recovery in the larger time frame. The improvements achieved through adaptive droop and model predictive control had a smaller effect on the frequency recovery time, but they both required fine-tuned parameters and more computational time. The grid-forming inverters consistently provided more effective performance. Grid-forming inverters have both instantaneous frequency and voltage stability; they behave like virtual synchronous machines. The performance of the distributed approaches was successful; however, they were reliant on a trusted communication network, and solutions based on multi-agent systems offered the best potential for developed systems, with an increase in cooperative resilience through disturbance management. The overall comparative evaluation showed the potential for the most robust performance for assessed low-inertia disturbance scenarios with the collective combination of multiple resilient approaches.

7.3 Balancing robustness, cost, and complexity

Resilient control schemes can be beneficial; however, there are a number of trade-offs that must be considered. When robustness is improved through advanced control schemes, such as grid-forming inverters and adaptive MPC, there will almost certainly be increased costs in the form of hardware upgrades, communications, and computational costs. An alternative approach might be simpler solutions like synthetic inertia, which are cheaper to implement, but may not sufficiently support a power system during extreme disturbances or periods of high renewable penetration. Distributed and multi-agent control architectures can further aid scalability and evolving systems; however, they can add significantly to system complexity, coordination, and cybersecurity concerns. These trade-offs highlight the need for resilient control schemes to be appropriate with regard to the power systems' collective situational and systemic needs and limitations. Decision makers will need to find the appropriate balance of robustness, economic perspective, and operational complexity to ensure that low-inertia renewable-based grids remain stable and sustainable in the future.

8 Conclusion

This study has confirmed that resilient control approaches are incredibly important for the stability and reliability of low-inertia renewable power systems. We note all the strategies captured by resilient control, such as synthetic inertia emulation, margin-controlled adaptive and robust frequency control, grid-forming inverters, and distributed multi-agent architecture (consensus) of multi-agents will tremendously improve frequency response, reduce RoCoF, and improve stability margins compared to traditional procedures. These approaches also confirm resilient control can mitigate issues presented by low system inertia, as well as challenge operators to revise their regulatory environments and manufacturers to embed resilient signal processing capabilities into renewable devices. In summary, future research to develop standardized resilient control approaches, AI-enabled advanced predictive frameworks, and field demonstrations will be important first steps to transition these solutions from conceptual responses to roll-out at scale, to ensure renewable-dominant grid purposes are adaptive, secure, and sustainable.

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