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Inertia Improvement Strategies for Power Systems Dominated by Renewable Energy

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ABSTRACT

As renewable energy dominates power systems, converter-connected generating units and loads reduce system inertia. System behaviour change causes stability, control, and operating issues for grid operators. Understanding inertia in renewable-dominated environments demands much investigation. We must redefine system inertia since renewable energy sources can now supply virtual (or synthetic) inertia.

This report summarizes high-renewable energy power system inertia improvement studies. System operators' low-inertia system management difficulties and solutions are examined. The term should encompass modern grids' various system inertias. Recent studies reveal that lower inertia greatly affects frequency stability. Strategies and procedures in this study can mitigate these consequences.

1. Introduction

In 2015, EU-28 wind and solar energy capacities reached 128.8 GW and 87.9 GW, respectively, making up 14.1% and 9.7% of Europe's electricity generation. With additional renewable capacity planned for 2020 targets, many countries, including Spain, Portugal, Ireland, Germany, and Denmark, saw renewable energy contribute over 15% to their total electricity consumption, with some systems even achieving 50% instantaneous renewable penetration.

The power system faces challenges from fast renewable integration, aging infrastructure, and rising consumption. Unlike traditional generation, inverter-based renewable sources contribute little to system inertia, leading to greater frequency volatility. Inertia, crucial for grid stability and frequency control, is reduced with increased renewable energy adoption, making the grid more vulnerable to imbalances. Emerging control systems simulate inertia by enabling renewable devices to discharge kinetic energy, improving grid stability.

IJAMSR

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Most studies focus on small, isolated systems with low inertia, but larger interconnected grids may face similar issues in the future. This paper discusses inertia in current and future power systems, analyzing its impact and exploring solutions to maintain resilience as synchronous inertia decreases.

Structure: Section 2 discusses traditional and renewable system inertia. Sections 3 and 4 evaluate synchronous and converter-connected generation inertia. Section 5 addresses stability with reduced synchronous inertia. Section 6 proposes solutions for low-inertia operation, and Section 7 concludes with findings and recommendations.

2. Inertia in Traditional and Future Power Systems

Inertia is the resistance of physical objects to changes in speed and direction. Traditional power systems rely on synchronous, turbine, and induction generators, where the moment of inertia measures resistance to speed variations. These large generators and turbines contribute most of the system's inertia. As these machines are connected to the power source, their mechanical rotational speed (ωg) is directly linked to the electrical frequency (ωe), defining the generators' dynamic behavior.

$$\frac{\mathrm{d}J_{\mathrm{SG}} \cdot \omega_{\mathrm{e}}}{\mathrm{d}t} = T_{\mathrm{m}} - T_{\mathrm{e}}$$

Electrical and mechanical torques, T_{e} and T_{m}, increase inertia in renewable energy-based power systems. The combined inertia of the generator and turbine, JSG, is adjusted to the electrical frequency through pole pair analysis. To reduce inertia in such grids, power system engineering often expresses the swing equation in terms of power instead of torque.

$$H_{\mathrm{SG}} = \frac{\frac{J_{\mathrm{SG}} \cdot \omega_{\mathrm{e},0}^{2}}{2}}{S_{\mathrm{SG}}} = \frac{E_{\mathrm{SG}}}{S_{\mathrm{SG}}}$$

The left side of Equation 2 represents the rate of change in kinetic energy of rotating components like turbines and generators in renewable energy-based power systems. Kinetic energy, relative to generator power rating, is measured by the inertia constant HSG. This constant reflects how long a generator can maintain its rated power from its rotating mass's kinetic energy. Enhancing system stability with high renewable penetration requires improving or adjusting this inertia.

$$2 \cdot H_{\mathrm{SG}} \cdot \bar{\omega}_{\mathrm{e}} \cdot \frac{\mathrm{d}\bar{\omega}_{\mathrm{e}}}{\mathrm{d}t} = \bar{P}_{\mathrm{m}} - \bar{P}_{\mathrm{e}}$$

Using SSG, the generator's apparent power and nominal angular system frequency are ωe,0. To convert equation 2 to per-unit values (‾), use equation 3:

$$2 \cdot H_{\mathrm{sys}} \cdot \bar{\omega}_{\mathrm{e}} \cdot \frac{\mathrm{d}\bar{\omega}_{\mathrm{e}}}{\mathrm{d}t} = \bar{P}_{\mathrm{g}} - \bar{P}_{\mathrm{l}}$$

I J A M S R
International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

The system frequency is a global parameter; thus, all power units can be grouped into one mass model:

$$2 \cdot H_{\mathrm{sys}} \cdot \frac{\mathrm{d}\bar{\omega}_{\mathrm{e}}}{\mathrm{d}t} = \bar{P}_{\mathrm{g}} - \bar{P}_{\mathrm{l}}$$

with

$$H_{\mathrm{sys}} = \frac{\sum H_{\mathrm{SG}} \cdot S_{\mathrm{G}}}{\sum S_{\mathrm{SG}}} = \frac{\sum E_{\mathrm{SG}}}{S_{\mathrm{sys}}}$$

Consider the inertia constant of the power system (assuming solely synchronous generation, ignoring load and embedded generation), total produced power (P¯g), and total load power (P¯l). This paper defines Ssys as the system's total generation capacity.

Assuming $\bar{\omega}_{\mathrm{e}} \approx 1$, leads finally to:

$$2 \cdot H_{\mathrm{sys}} \cdot \frac{\mathrm{d}\bar{\omega}_{\mathrm{e}}}{\mathrm{d}t} = \bar{P}_{\mathrm{g}} - \bar{P}_{\mathrm{l}}$$

The total inertia of a traditional power system refers to the kinetic energy exchanged between synchronously connected machines to counteract frequency changes resulting from generation and demand imbalances. Power imbalances transfer this kinetic energy.

$$\Delta E = \sum \Delta E_{\mathrm{SG}} = \int (P_{\mathrm{g}} - P_{\mathrm{l}})\,\mathrm{d}t$$

In renewable energy-dominated power systems, energy dynamics after a power imbalance are vital for system stability. In Figure 2, block areas represent system kinetic energy, while width and height relate to moment of inertia ($\sum J_{\mathrm{SG}}$) and electrical frequency squared ($\omega_{e,0}$). The gray zone indicates kinetic energy at nominal frequency. System operating frequencies are limited, causing kinetic energy fluctuations. Synchronous generators balance power shortages by releasing kinetic energy (Eq. 8). If this energy is depleted without quick actions, such as raising generating set points, system instability may occur. Low-inertia systems with significant renewable energy penetration need improved inertial responses for frequency stability.

As renewable energy grows, traditional synchronous units may be replaced due to lower costs. Renewable sources, connected via power electronic converters, do not contribute system inertia. Unlike traditional plants, which use kinetic energy to stabilize frequency, converter-based renewables decouple rotational speed and frequency. Additionally, the rise of HVDC transmission networks, which disconnect AC grids, further reduces system inertia. In future grids, converter-based generation will likely replace synchronous units, decreasing system inertia. With lower inertia, systems are more vulnerable to disturbances, with higher rates of frequency change (ROCOF) and lower minimum frequencies.

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Power electronic converters typically don't respond to frequency changes unless designed to do so. However, they can simulate virtual inertia through control strategies, as shown in Figure 3. Hybrid systems with both synchronous and converter-based generation must redefine system inertia (H_sys) to account for both physical and synthetic contributions.

$$H_{\mathrm{sys}} = \frac{\sum E_{\mathrm{SG}} + \sum \frac{J_{\mathrm{V}} \cdot \omega_e^2}{2}}{S_{\mathrm{sys}}} = \frac{\sum E_{\mathrm{SG}} + \sum E_{\mathrm{V}}}{S_{\mathrm{sys}}}$$

Power sources like flywheels, batteries, capacitors, and others contribute to system inertia by disconnecting generation units from the grid. PV systems use batteries, while wind turbines rely on blades, gearboxes, and generator kinetic energy. Deloading generation units for reserves is another approach. However, these exchanges are constrained by converter limitations, minimum rotor speeds, and turbine blade acceleration/deceleration.

In future power systems, inertia helps resist frequency shifts due to generation-demand mismatches. Virtual and synchronous inertia from converter-connected units and grid machines create this resistance. Converter-connected generation can partially compensate for synchronous inertia loss using virtual inertia, reducing frequency deviations compared to systems without it.

Virtual inertia, as shown in Figure 2 (System C), supports power balancing by providing energy through virtual inertial response (∑ΔEV). This maintains a higher frequency frequency $[\omega_{e,1}]_C$ at $t = t_1$ compared to systems without virtual inertia. Each converter involved can utilize storage, wind, power reserves, or HVDC-linked systems' kinetic energy, based on the system setup.

Load inertia in renewable-powered systems is less studied. Induction motors and fans can generate system inertia by adjusting power output with frequency. In future systems, loads should produce less inertia, with low response mainly due to variable frequency drives.

3. Inertia from Synchronous Connected Generation and Power System Load

To calculate the total inertia of a renewable energy-based power system, data on generation units and loads are needed. Inertia from large conventional power plants is typically evaluated first. However, many power system studies ignore or assume constant inertia due to limited data on load and embedded generation. Inertia can be calculated using frequency measurements, as stated in the third section.

3.1 Inertia From Synchronous Connected Generation

Older power systems rely on the inertia constant of large conventional generators, which stabilizes the system. This constant is influenced by the machine's speed, size, and type. Generators with similar technologies have an inversely proportional relationship between inertia constant and power rating. In renewable energy-based systems, system inertia fluctuates due to dynamic unit commitment, fuel types, and generation schedules, leading to variability. TSO databases usually use simplified or uniform inertia values, and contributions from synchronous generators in distribution networks are rarely documented. In renewable-heavy grids, improving inertia is crucial for stability.

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3.2 Load Inertia

Renewable energy-based power systems require precise measurement and enhancement of system inertia, which depends on load dynamics and types. Grid-connected motor loads, being directly coupled, contribute to inertia as their rotational speed is influenced by system frequency, unlike pure resistive loads that are frequency-independent. Effective solutions for inertia improvement should account for load types and their contributions, considering load variability, voltage, and frequency fluctuations. System studies model the demands of constant impedance, current, power, and induction motors, with careful parameterization of active and reactive power responses. One study [21] estimated load inertia by subtracting synchronous machine inertia from system inertia, revealing that load inertia constants in Irish and Northern Irish networks were less than one second and varied with system demand. These findings highlight the importance of accurate load modeling and dynamic analysis in renewable-dominated power systems.

3.3 Measuring and Estimating System Inertia

Frequency measurements have been used to assess system inertia after large power imbalances in renewable-based networks, with ROCOF and the swing equation being common estimation methods. However, challenges like filtering noisy inputs, selecting ROCOF sampling rates, and determining disturbance onset complicate inertia calculation. Traditional swing equations only approximate frequency behavior during the initial moments after an imbalance, as governor responses and control actions later influence frequency dynamics. A new approach, using synchrophasor data, reveals that embedded generation and load contribute 8-25% of the UK's system inertia, suggesting that decentralized renewable sources could help improve inertia in such systems.

4. Inertia from Converter Connected Generation

Converter-connected generators store kinetic energy but do not mechanically link to the grid in renewable energy-dominated power networks. This and other energy storage enhance system inertia. Strategy is covered here. Compare renewable energy units' kinetic energy to typical power plants. Exchanging and controlling stored energy for grid operation with low synchronous inertia is next examined.

4.1 Amount of Stored Energy in Converter Connected Generation

Modern renewable energy networks, mainly powered by wind and photovoltaic (PV) systems, generate most of their power through converter connections. Wind turbines contribute to system inertia through their blades, gearboxes, and generators, storing kinetic energy. In contrast, PV systems lack stored energy, except for capacitors, and have limited inertial contribution. The inertia of wind turbines varies with design, size, and gearbox, with a typical 2 MW turbine storing 12 MJ of kinetic energy. Wind turbine inertia values $H_{\mathrm{WT}} \approx$ 3-6 seconds, similar to traditional generators. Wind turbine inertia fluctuates based on operational speed, with low wind speeds reducing kinetic energy by up to 60%. Wind turbine inertia contributions vary, with less than 50% of maximum kinetic energy available for half of the operational time. PV systems are inertial-free, requiring alternatives like batteries and supercapacitors for synthetic inertia. Deloading PV arrays below MPPT voltage can create an inertial response buffer, though it may reduce energy yield. Studies show that deloading is more cost-effective than battery integration for frequency control. These technologies are crucial for improving inertia in renewable energy-dominated power networks.

4.2 Virtual Inertia from Converter Connected Generation

Many controller algorithms provide virtual inertia in renewable energy systems, mimicking synchronous generators by adjusting active power with frequency, as shown in Figure 3. However, converter-based resources differ from traditional generators, as they lack accurate physical inertia or stored energy. The virtual inertia constant, JV, depends on the renewable source and operational position. While it can be adjusted to meet system needs, practical limits are required for stability.

High virtual inertia can slow wind turbine blades, reducing lift or causing stalling. Increasing JV allows more energy release during frequency events compared to synchronous machines. Wind turbines at maximum rotor speed release 5.25 times more kinetic energy than synchronous machines with the same inertia constants when slowing down.

Adding converter-connected renewable energy doesn't reduce system inertia. Additional control methods are needed to harness kinetic energy due to operational restrictions. Converter controls also introduce delays in frequency detection, which slow inertial response. Various inertial response methods, like droop-based and step-response strategies, have been developed to improve energy recovery after inertia support. Renewable-dominated systems exhibit distinct inertial behavior compared to traditional synchronous systems due to diverse power responses following disturbances.

5. Impact of Reduced Synchronous Inertia on Power System Stability and Control

Renewable energy-based power systems must evaluate the effects of reduced synchronous inertia on stability and control. Figure 6 shows the influence of synchronous inertia on system behavior, ranging from milliseconds to seconds (grey band), highlighting its role in frequency and rotor angle stability. Primary voltage control and under-load tap changer control are excluded, as inertia does not impact voltage stability. The focus is on methods to enhance system inertia, excluding sub-synchronous resonance.

5.1 Rotor-Angle Stability

Inertia stabilizes rotor angles in power systems, ensuring synchronous generator operation after disturbances. Small-signal stability is assessed by the system's oscillatory mode eigenvalues. The SMIB model shows that reducing machine inertia speeds up electromechanical modes and reduces damping, leading to faster angular displacements after disturbances.

Renewable energy sources like wind and PV units affect system dynamics but don't cause electromechanical oscillations. Their impact on small-signal stability depends on factors like penetration level, location, and control methods.

System inertia affects transient stability during significant shocks. Reduced inertia increases rotor angle swings, risking transient instability. In networks with high converter-connected generation, improved fault-ride-through and reactive power support can help. Conventional units as synchronous condensers can restore inertia.

Studies suggest DFIGs can stabilize or destabilize wind integration depending on grid layout. Advanced controllers improve transient stability by assisting voltage and reactive power during failures. High PV penetration impacts transient stability, with fault-ride-through being crucial for system stability.

5.2 Frequency Stability

Power system frequency stability relies on balancing generation and load, with reduced synchronous inertia making it harder to maintain frequency. Without quick restoration, frequency fluctuations can lead to generator or load tripping. Synchronous generators help by adjusting their kinetic energy, allowing time for plant governors to act. Machines with lower inertia experience larger rotor swings, dampened by network losses and stabilizers. Governors adjust power to stabilize frequency, though small deviations may persist.

Systems with low inertia or converter-connected generators have weaker inertial responses, affecting ROCOF and nadir frequency, which can trigger protection devices. High converter generation, like wind and solar, worsens nadir frequency, while hydroelectric plants' delayed responses add to the problem. Governor control has less time to act, risking load shedding or generation loss.

ROCOF relays prevent islanding during grid failure, but high ROCOF in converter-dominant systems can cause cascading outages. Adjusting relay criteria for high wind penetration and allowing generators to handle higher ROCOF is advised. Repeated high ROCOF can damage synchronous generators, reducing system reliability.

6. Operation of Systems with Low Synchronous Inertia

Low synchronous inertia in renewable-dominated power systems creates challenges for frequency control and high ROCOF, particularly in smaller, isolated grids. These grids, which are more unstable, could serve as models for larger low-inertia systems. In the early 21st century, isolated systems limited converter-connected generation to 20-50% to avoid operational issues, with countries like Greece and Ireland setting caps on wind generation. As converter-connected generation increased, concerns grew. A study by EirGrid showed that wind penetration could reach 60-75% without major issues, and by 2020, wind curtailment in Ireland was estimated at 7-14%. Strategies like the Irish DS3 program explore solutions such as modifying grid equipment, using virtual inertia, and flexible plants to support higher converter-connected generation. The REserviceS initiative also considers virtual inertia as a grid support service.

7. Conclusion

This research explores inertia in power systems, its impact on stability, and how reduced synchronous inertia in renewable energy grids affects system performance. Future power networks will combine conventional power plant inertia with inertia from converter-connected renewable generation. These converters add inertia through kinetic energy buffers. As frequency stability becomes a growing concern, the study examines the effects of reduced inertia, highlighting the risk of increased ROCOF and instability. The research calls for innovative methods to decrease synchronous inertia and better integrate renewable power, though optimal and cost-effective solutions remain uncertain.

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IJAMSR

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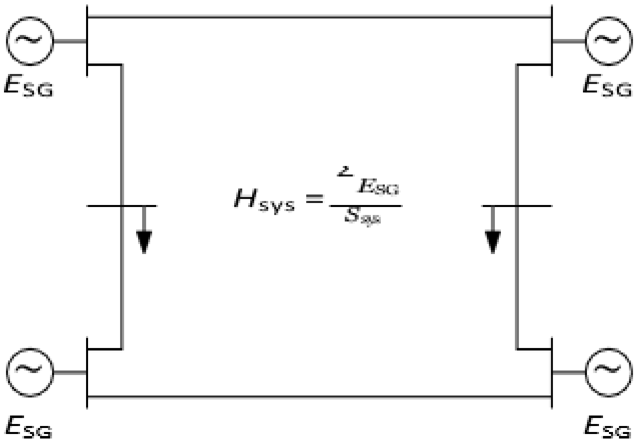
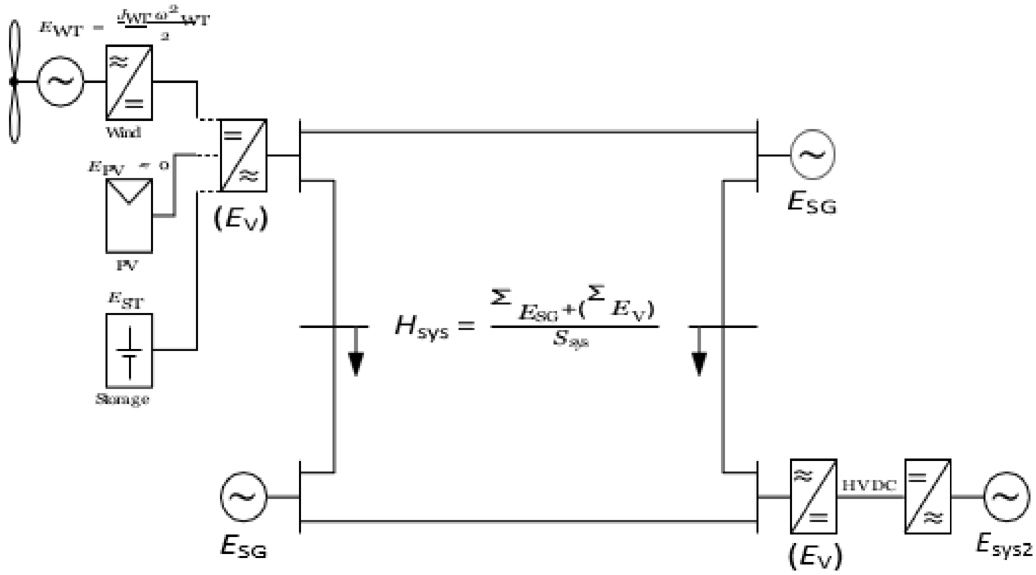


(a) Traditional Power System



(a) Future Power System

Figure 1: Inertia and (Kinetic) Energy Storage in Power Systems

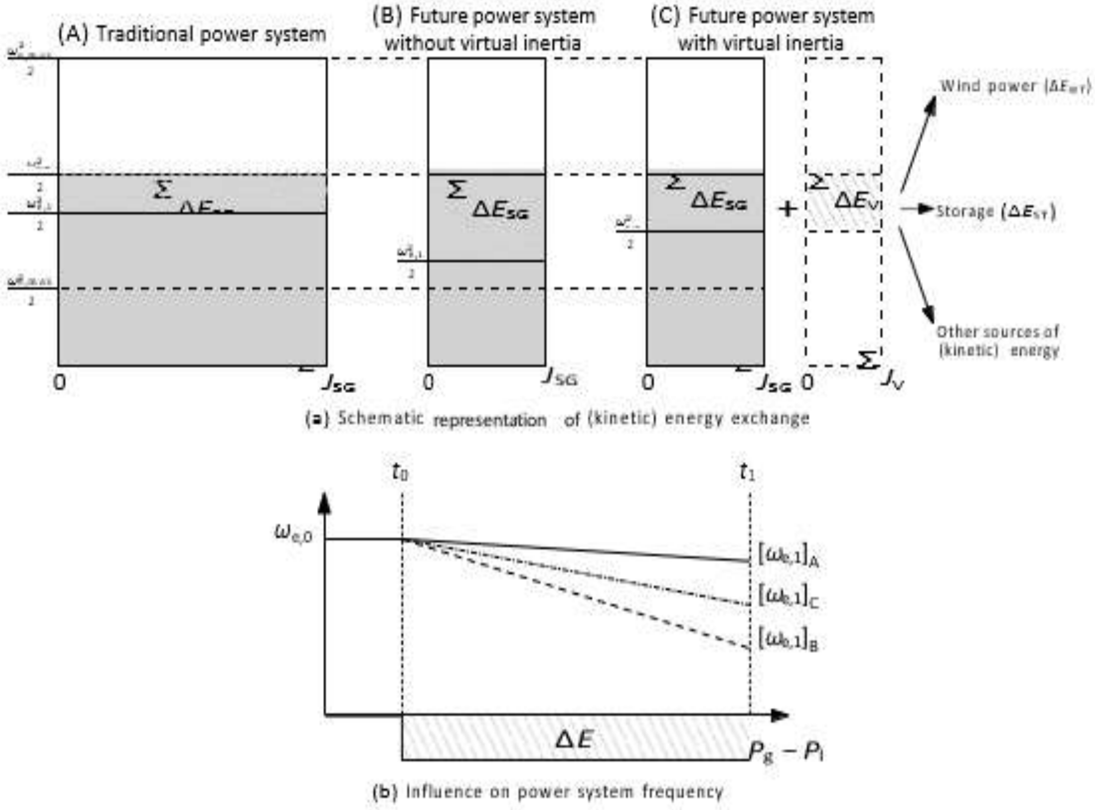


Figure 2: (Kinetic) Energy Exchange in Traditional and Future Power Systems After a Power Imbalance

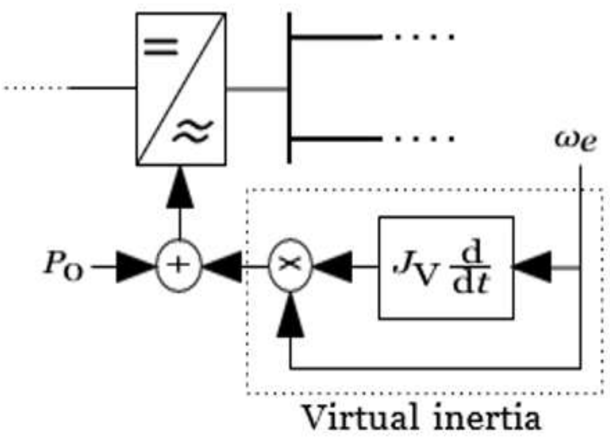


Figure 3: Virtual Inertia Controller

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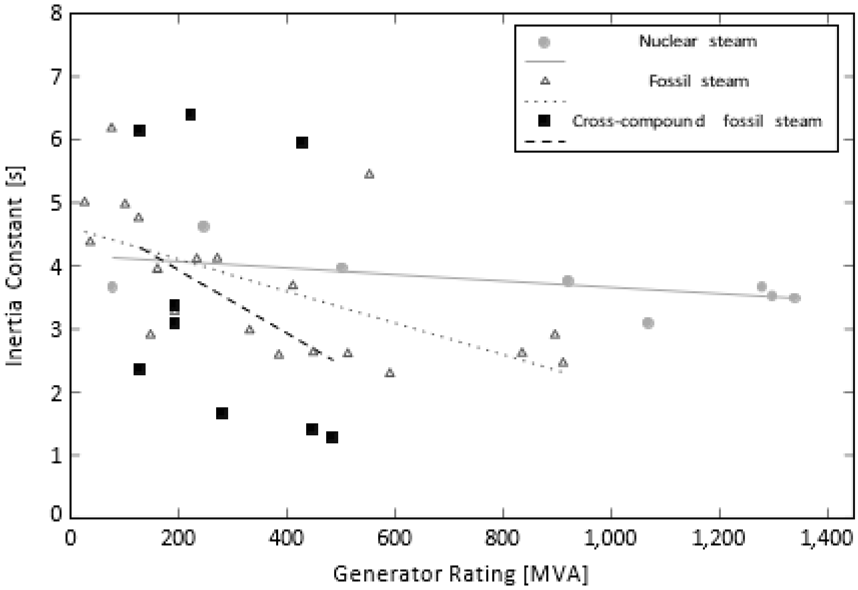

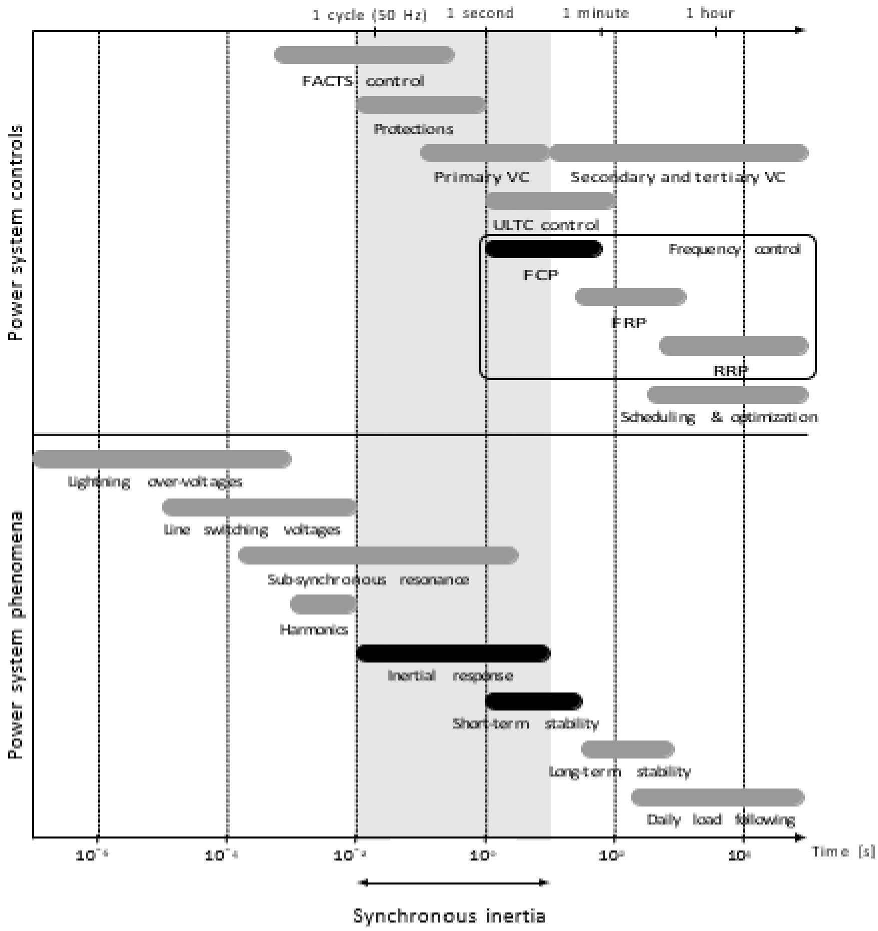

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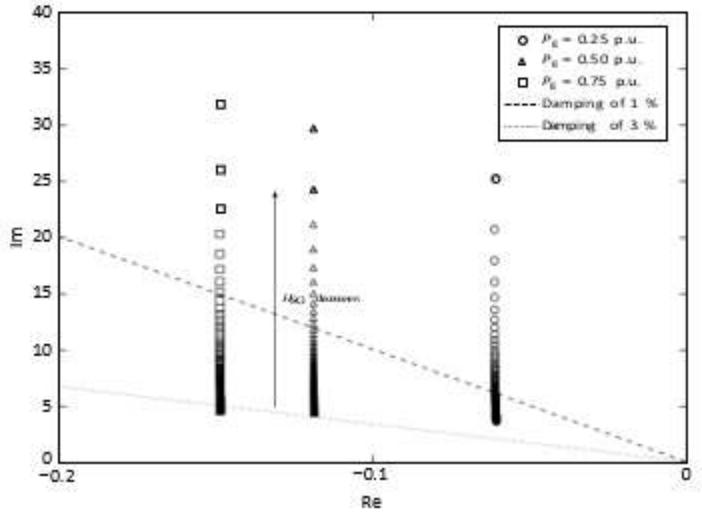

Figure 4: Electro-Mechanical Modes for A Single Machine Infinite Bus System in Function of Inertia and Operating Point

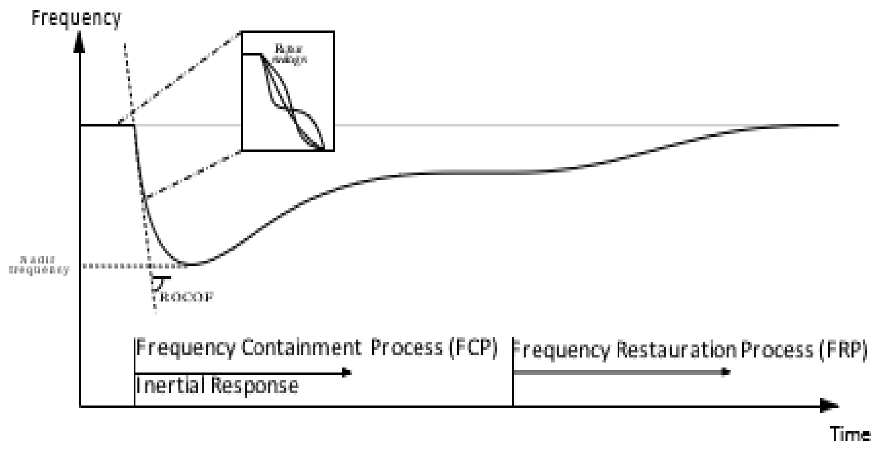

Figure 8: Classification of frequency control mechanisms

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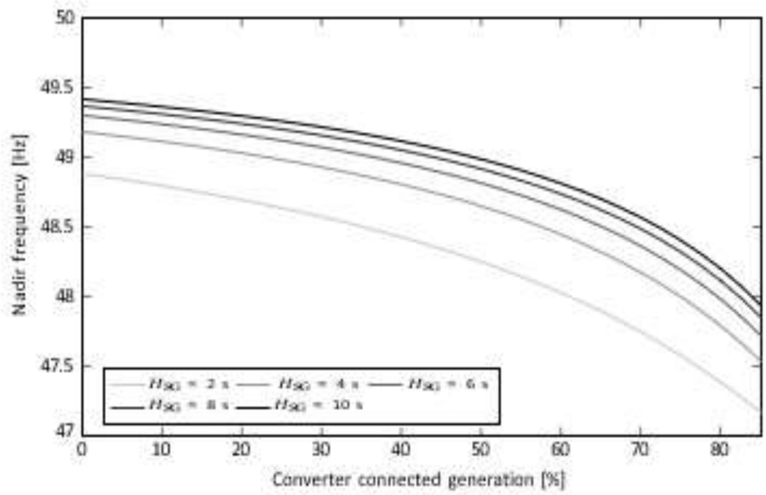
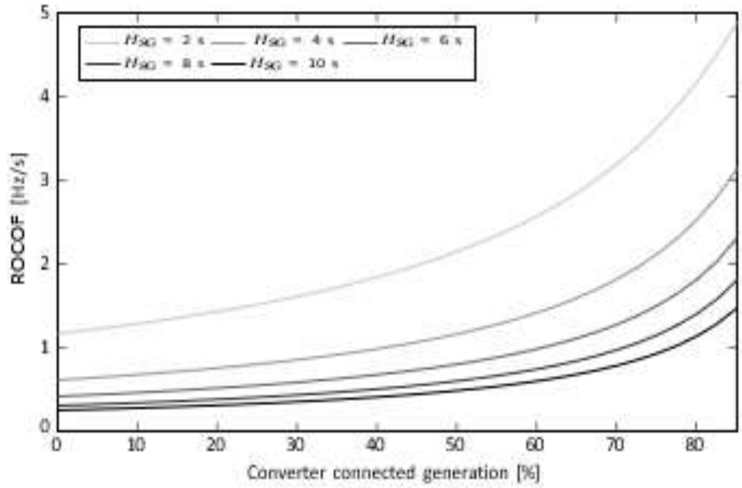


(a) Nadir frequency in function of different levels of converter connected generation



(a) ROCOF measured over 500 ms in function of different levels of converter connected generation

Figure 5: Nadir and ROCOF in function of converter connected generation for a power imbalance of 0.1 p.u., assuming an equal share of thermal and hydro power plants. The inertia constants of the synchronous connected units are varied between 2 and 10 s.

IJAMSR

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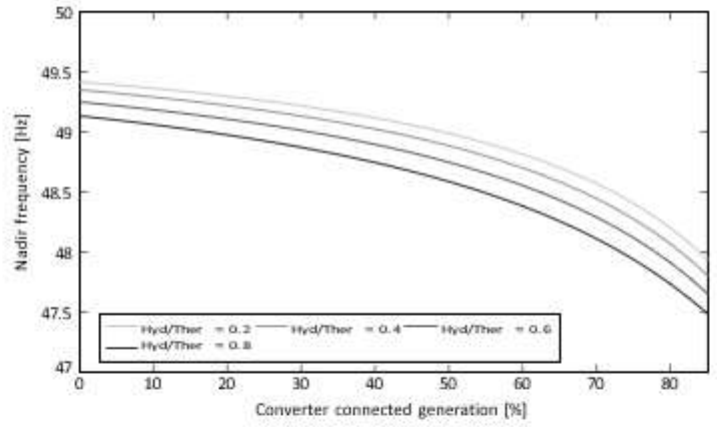

Figure 6: Nadir frequency for a power imbalance of 0.1 p.u., in function of different levels of converter connected generation & increasing share of hydro power. The inertia constants of the synchronous connected units are equal to 6 s.

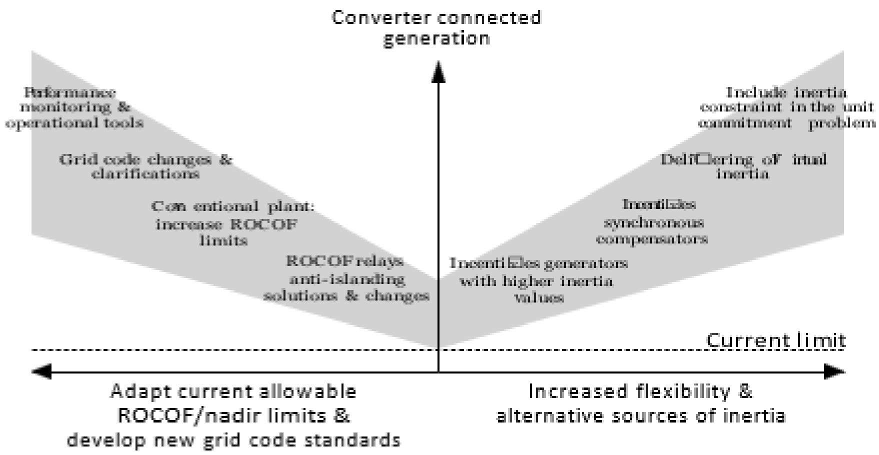

Figure 11: Different proposed options to operate a system with low synchronous inertia in a safe and secure way