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The Impacts of Renewable Energy Sources: A Review on Grid Inertia and Frequency Regulation

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ABSTRACT

The power system is gradually transitioning into low inertia due to integrating substantial intermittency quantity of converter-based renewable energy sources, such as wind and photovoltaic power, into the current power grid network. This integration presents significant inertia and frequency control challenges to the network as a result of a decrease in the percentage of synchronous generators. Moreover, faster frequency deviations are posed by the mismatch between the supply and demand during contingencies, which creates difficulties in preserving the frequency stability of the power system. This research explores the impacts of renewable energy sources (RESs) on grid inertia and frequency management as key parts of preserving the power system's stability. Furthermore, the research article proposes mitigation ways to optimize both conventional synchronous generators and synthetic inertia for consistent and dependable functioning of the grid network while accommodating a growing share of renewable energy. The mitigation measures examined in this review research paper are synthetic inertia, fast frequency response, and battery storage systems.

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INTRODUCTION

Fossil fuels using synchronous generators have been the dominant source of global electricity generation for some decades. According to International Renewable Energy Agency (IRENA) report of 2024, 60 % of the world's share of electricity generation was from fossil fuels by 2023 and is expected to drop to 30 % by 2030 (IRENA, 2024a). Using fossil fuels for energy generation harms the environment and leads to direct and indirect negative economic effects. Furthermore, fossil fuels are finite because they are non-renewable hence, they do not naturally replenish quickly enough for human usage indefinitely. With this depletion of fossil fuel reserves and environmental concerns, synchronous generator-based energy sources (SGESs) have given way to inverter-based renewable energy sources (IRESs) in the modern power grid (Saha et al., 2023; Saleem, Saha, Izhar, et al., 2024). Figure 1 illustrates the transition from a conventional grid characterized by high inertia to a contemporary grid with low inertia, attributable to the substantial integration of renewable energy sources.

This shows that the dependability of high kinetic energy stored in the rotating machines is significantly diminished.

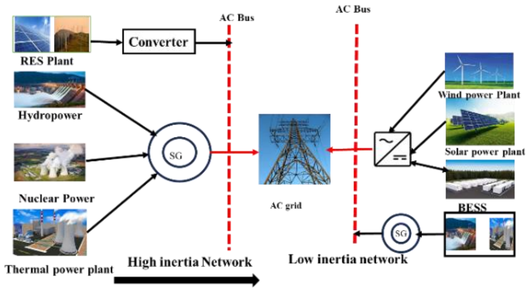

Figure.1. Conventional to future power plants transition.

Africa projects an increase in renewable energy share from 56 GW in 2022 to 300 GW by 2030 (IRENA, 2024b). Tanzania aims to generate 50% of its energy from renewable sources by 2030, prioritizing solar, biomass, and hydropower (Kurniawati, 2017). The solar installed capacity in Tanzania was only 16 MW in 2023 (IRENA, 2024a). Notably, there is an ongoing Kishapu Solar project of 150 MW (Citizen, 2023) which will be integrated into the grid after its completion. Improvements in technology, operational effectiveness, and cost competitiveness have benefited renewable energy and made it a more appealing option globally. Renewable energy sources (RESs) such as wind and solar have undergone extensive research and are now employed in numerous power plants (Hassan et al., 2024; Mwasilu & Jung, 2019). Among other renewable energy sources, worldwide solar contributes 31 % of all installed renewable energy following hydropower (Pourasl et al., 2023). This has been possible because of some benefits such as technological advancements, cost decline, and environmental benefits. Unlike synchronous machines-based energy sources, RESs such as solar do not have any rotating mass to provide kinetic energy support and are decoupled from the grid network; therefore, they don't contribute to the grid inertia. This resulted in a decline in overall grid inertia.

The overall inertia in a power system dominated by synchronous machines is high due to the kinetic energy stored in their rotating parts. On sudden load variations, the stored kinetic energy is used as a reservoir to inject or absorb power to the network (Monshizadeh et al., 2017; Wu et al., 2021; C. Zhang et al., 2021), thereby maintaining the system frequency stability. The overall system inertia is highly reduced for the system with high penetration of RESs connected via the converters. This affects the system inertia and frequency stability (Sun et al., 2020; Xiong et al., 2021) as small power imbalances lead to frequency deviation above the permissible limit to the extent of causing power outages, load shedding, and even complete power system failure (Prabhakar et al., 2022a; Yegon & Singh, 2024).

The integration of renewable energy sources (RESs), such as wind and solar (PV) reduces the system's overall inertia and increases the rate of change of frequency (RoCoF). Despite their inertia, variable-speed wind turbines (WTs) cannot improve frequency response or contribute to inertia since they are connected to the network through power electronic converters, which essentially decouple them from the system (Alam et al., 2020). Furthermore, solar power plants cannot contribute any inertia to the power system (Alam et al., 2020; Nerkar et al., 2023), this tends to degrade the frequency response that the conventional synchronous generators are substituted. Generally, due to the integration of intermittent and unpredictable power sources from IBRESs, the system inertia decreases and becomes highly variable (Zhao et al., 2019), and therefore frequency stability issues arise.

The effects of high levels of renewable energy penetration on the grid and their consequences on frequency stability and inertia have been the subject of several research studies that have been published recently. The low-inertia power grids that result from the high penetration of inverter-dominated energy sources have been discussed by (Banks et al., 2017; Saha et al., 2023; Stojković & Stefanov, 2022), to mention a few of them. These papers provide a comprehensive overview of the novel issues encountered by grid operators in maintaining frequency stability when inertia diminishes. These publications offer potential mitigation measures for grid operators to address these issues.

The increase of intermittent and unpredictable linked to renewable and converter-based energy generations has led to difficulties in power system frequency control (Heylen et al., 2021). Therefore, for secured and reliable operation of a low-inertia power system with high penetration of RESs, the estimation and forecasting of system inertia is crucial. Corresponding to estimating and forecasting the system inertia, the energy storage system must be available just in case the inertia is low. This paper presents the inertia estimation methods and the energy storage system as the mitigation means for stable and reliable grid network frequency.

METHODS AND MATERIALS

Impacts of Low Inertia RESs Dominated Power Grid

Rotating elements such as motors, generators, and other machinery are a power system's primary source of inertia. The capacity of the power grid to sustain stable operational conditions and lessen the impact of disruptions can be attributed to the inertia of these rotating components, which offer additional energy reserves when the load changes. Inertia in conventional power systems is defined as resistance to synchronous generator speed changes, that are equal to the system frequency, and the inertia of a synchronous generator is expressed as;

$$J = r^2 \int dm = mr^2 \quad (1)$$

Where J is the moment of inertia of the synchronous generator and turbine in kg-m^2, r denotes the radius of the synchronous generator's spinning component in meters (m) and m represents the mass in kilograms (kg). The power system inertia is the equivalent of the retained rotational kinetic energy within the directly linked spinning masses of the grid, expressed in terms of rotational velocity as;

$$E_{EK} = \sum_{1}^{N} \frac{1}{2} J_i \omega_i{}^2 \quad (2)$$

where J_i and ωi are the rotational inertia and the speed of the i^{th} -generators interconnected respectively. The equivalent system inertia is as indicated in Equation (3) and graphically illustrated in Figure 2.

$$H_{sys} = \frac{1}{S_{sys}} \sum_{i=1}^{N} H_{sg,i} . S_{sg,i} \quad (3)$$

where;

H_{sys} represents the equivalent inertia constant of the power system, S_{sys} is the rated capacity of the system, $H_{sg,i}$ is the inertia constant of a synchronous generator based on its apparent power, S_{sg} is the rated apparent power of i^{th} synchronous generators in MVA and N represent the number of generators connected to the system.

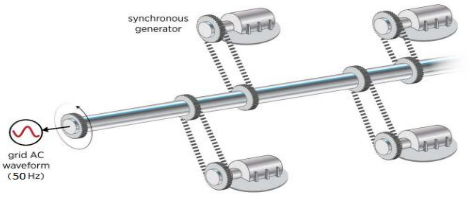

Figure 2: **Power system with synchronous generators (Denholm et al., 2020)**.

Integrating renewable energy sources (RESs) greatly affects grid stability, leading to high-frequency deviations. The system inertia decreases and becomes highly variable due to inverter-based renewable energy sources. The frequency behavior of the test power grid at varying RES penetration levels is used to analyze the effects of decreased grid inertia (Saleem, et al., 2024).

Table 1: Recent years' real accident examples related to low inertial in the grid systems

S/No:	Incident name & Year	Cause	References
1	Great Britain -2019	Failure of 730 MW, leads to the loss of 1878 MW	(Hong et al., 2021; Song et al., 2023)
2	Texas USA, 2021	Failure of 24000 MW, leads to the loss of 52277 MW	
3	Australia, 2016	Lack of rotational inertia leads to high RoCoF	(Wachter et al., 2024)
4	Netherlands, 2000	High penetration of DERs	

Essentially, virtual inertia mimics the inertia of conventional synchronous generators by utilizing power electronics, renewable energy sources, control algorithms, and energy storage systems (ESS) such as batteries (Mufti, 2024). With the integration of RESs, the electrical power system's natural inertia is reduced due to incorporating a non-rotating inertia. The total system inertia incorporating the power electronic converter generator is described as;

$$H_{sys} = \frac{\sum_{i=1}^{Nsg} H_{sg,i}.S_{B,i} + \sum_{j=1}^{Ncig} H_{cig}.S_{B,j}}{\sum_{i=1}^{Nsg} S_{B.i} + \sum_{j=1}^{Ncig} S_{B.j}} \quad (4)$$

where;

- H_{sys} represents the equivalent inertia constant of the power system
- $S_{B,i}$ denotes the rated apparent power of i^{th} synchronous generator in MVA
- $S_{B,j}$ denotes the rated apparent power of j^{th} power converter interfaced generators in MVA
- H_{sg} is the inertia constant of a synchronous generator based on its apparent power
- H_{cig} is the inertia constant of the power converter-interfaced generator

The equivalent inertia in Equation (4) can be further graphically demonstrated using Figure 3.

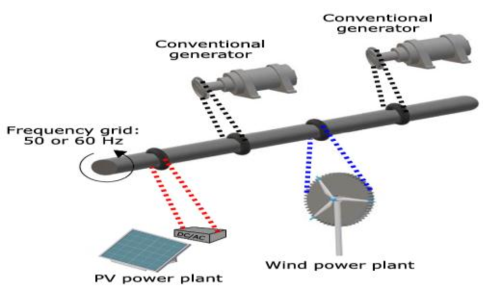

Figure 3: Power system with SGs and RESs (Buckner et al., 2016)

Low Inertia Cases in Power Systems

The use of intermittent renewable energy sources reduces the overall power system inertia. In a system with less inertia, when subjected to a disturbance, its frequency change rate becomes high. This may lead to triggering the protection relaying system, such as under-frequency load shedding, which may disconnect a large part of the network. Table 1 narrates a few accident examples related to low inertia as a result of RES integration and a lack of backup arrangements.

Frequency Response on RES-Dominated Power Grid

When converter-connected generators replace conventional synchronous generators, the power system's available rotational inertia is reduced. This causes faster frequency dynamics and, as a result, less stable frequency behavior. Inertia decreases lead to high RoCoF and frequency nadir in the power network. Figure 4 depicts how the system frequency could alter in high and low-inertia conditions after a contingency event. This elucidates the function of system inertia in frequency control. Due to the continuous variations between load and generation, frequency and RoCoF in the power system are always fluctuating, but on reduced system inertia, the quantities of variations may increase beyond the allowable limits. When the measured values of RoCoF are beyond the predefined values, RoCoF relays are triggered. Integration of converter-based generation has led to changes in RoCoF relay settings to accommodate the variations caused by the

RESs. A good example is Great Britain, which used 0.125 Hz/s during conventional power systems but now uses 1 Hz/s with a delay time of 0.5 s (Hong et al., 2021). Notably, the primary frequency response (PFR) under low inertia which is due to RES integration is not quick enough to stop the frequency deviation (Wilson et al., 2019), consequently, supplementary inertia is necessary to sustain the system stability.

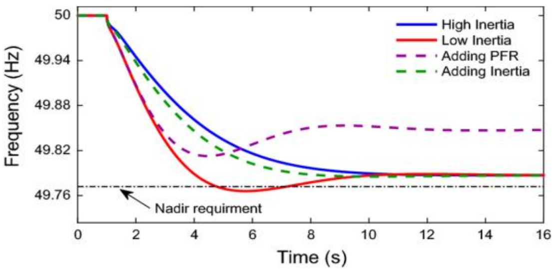

Figure 4: **System frequency response under lower system inertia (Rezkalla et al., 2018).**

RESULTS AND DISCUSSIONS

Inertia Estimation and Forecasting

Inertia estimation and forecasting are vital for maintaining grid stability, enhancing reliability, integrating renewable energy sources effectively, achieving economic efficiency, planning future grid upgrades, and meeting regulatory requirements. In instances of power disparities between load and generation, inertia becomes an important component in controlling the rate of change of frequency (RoCoF) and frequency nadir. Therefore, the inertia acts as the frequency counteract to the power disparities between generation and demand (Heylen et al., 2021). An accurate inertia estimation and the forecasting of the system help in understanding the dynamic response during the grid disturbances. Low statistical estimation errors indicate a strong and accurate relationship between the inertia estimation and the actual reference inertia. Low statistical measures such as mean absolute error (MAE), root mean square error (RMSE), and mean absolute percentage error (MAPE) are employed to evaluate the correctness of the inertia estimated values and the actual reference inertial values.

The inertia constant values of power systems must be evaluated and monitored for stability control. The predicted inertia values provide the power system operator with essential information regarding frequency nadir, and the rate of change of frequency (RoCoF). Corrective measures are implemented to lessen the effects of unanticipated power system frequency response. Offline, online, and predictive are the three main categories of inertia estimation approaches used as the mechanism of inertia monitoring and as the guide leading toward correct decisions.

Offline Inertia Estimation

Following disturbances in the system network, offline inertia estimate approaches are used to investigate and assess the values of constant inertia in the network. They estimate the network's inertia using past data or information, such as active power and frequency captured using a Phasor Measurement Unit (PMU) after the disruption or under normal operating conditions. The estimation algorithm is established from the disturbances or normal operating data recorded by the PMU for inertia estimation. Model-based and measurement-based methods are the two basic divisions of offline inertia estimation approaches (Tan et al., 2022). The model-based approach deals with single synchronous generator and regional system inertia estimation while the measurement-based deals with ambient data and large disturbance-based inertia estimation. The ambient data were used by (Makolo, et al., 2021; Tuttelberg et al., 2018; Zhang & Xu, 2017) to develop the algorithm that was used to estimate the power system inertia. On the other hand (Ashton et al., 2015; Chassin et al., 2005; Wall et al., 2012; Wall & Terzija, 2014; Zografos et al., 2018) they used disturbance data to develop the estimation algorithm for inertia estimation. The majority of offline inertia estimation (IE) approaches depend on the post-event data, their accuracy is low because transient/fault may cause changes to the RoCoF and frequency nadir. The error between 4.14% to 8.8 % for the simulation and 11.5 % for the actual system was achieved by (Makolo et al., 2021) on offline inertia estimation. Furthermore (Zografos & Ghandhari, 2016), an error of above 20 % was recorded. The estimation error experienced by the offline method can be reduced with online estimation methods, increasing the accuracy of inertia estimation.

Online Inertia Estimation

Smart grid technologies like synchronized wide-area observations have made it possible to calculate the system's inertia in real-time. These techniques use dynamic load behavior and ongoing fluctuations in renewable energy generation to calculate the system inertia. These techniques model the system utilizing its micro-disturbances using observations of ambient data from PMU (Prabhakar et al., 2022). PMUs are utilized to record the network's real-time measurements for inertia estimation (Makolo, et al., 2021). In (Zeng et al., 2020) using ambient data obtained from the PMUs, a dynamic model measuring the active power and bus frequency at the generation node was discovered. With no RES penetration, the highest relative inaccuracy of the identified inertia was below 5%. An error of 8.5 % was recorded by (Makolo, et al., 2021) on the online estimation with RESs penetration where the recorded data by the PMUs were passed through a non-causal Butterworth low pass filter. Generally, the online inertia estimation experiences some estimation errors due to noisy measurements from the PMU. The forecast estimation approach can reduce the estimation error experienced online. This leads to an increase in inertia estimation accuracy to monitor the power system stability.

Forecast Inertia Estimation

In anticipation of reduced power system inertia, especially the systems with high penetration of RESs, future predictions must be done. This assists the power system operators in planning for an alternative source of inertia in the network. The network's inertia value can be forecasted, allowing for the early adoption of suitable solutions by identifying when the network will be at risk. Long-recurrent convolutional neural network (LRCN) and graph convolutional neural network (GCN) networks, respectively, were used as the foundation for the inertia estimation approach (Tuo et al., 2022). The accuracy of 97.34 % and 98.15 % were achieved from the proposed models of LRCN and GCN respectively. On (Ramirez-Gonzalez et al., 2022) the residual neural network was applied for power system inertia estimation, and the absolute relative error below 5 % was attained between the actual and predictive inertia values. With significant integration of wind energy, the Artificial Neural Network (ANN) was used by (Paidi et al., 2020), where variables including active power from all synchronous generators (SGs), total active power generated by Renewable energy sources (RESs), and total dynamic induction motor all measured by phasor measurement units (PMUs) via wide area measuring systems (WAMS) were used as input. The absolute percentage estimation error of about 1 % was obtained between the predicted and actual inertia.

Overcoming the Challenges of Low-Systems Inertia

Various research has been undertaken to address the challenges of low-system inertia resulting from the replacement of conventional generators with converter-based generators. The necessity for faster energy injection to stop lowering frequency is driven by the high initial rate of change of frequency (RoCoF) in an interconnection due to diminishing system inertia(Hong et al., 2019; NREL, 2020). The faster frequency response (FFR) is the most promising solution to address low system inertia and elevated Rate of Change of Frequency (RoCoF) difficulties in a system with significant renewable integration. A quick-acting energy source, like a converter-interfaced energy storage system (ESS), can deliver power to efficiently reduce the frequency nadir and RoCoF (Meng et al., 2020). The fast-responding energy sources include supercapacitors, flywheels, and batteries. The energy storage source can be a standalone or hybrid, effectively and reliably controlling the system frequency.

Capacitors are devices that store energy between two charged plates. The storage capacity is enhanced due to an expanded charged surface area. Supercapacitors are recommended for small-scale and short-duration energy storage systems due to their self-discharge rate and elevated capital expense (Wong et al., 2019). The flywheel energy source technology system serves to maintain the system's stability by charging and discharging power. It operates on the principle of storing rotational energy by rapidly increasing the speed of a rotor (Olabi et al., 2021). Flywheel's limited energy storage capacity makes it unsuitable for long-term, long-duration applications (Khan et al., 2023). Batteries use an electrochemical energy storage system that allows chemical energy to be transformed into electrical energy during discharge and the opposite when charging. The variety of uses for batteries in the system, such as power system protection, power system control, spinning reserve, and power factor correction, makes them a potentially very lucrative energy storage technology (Wong et al., 2019). The procedures for frequency control scenarios with significant integration of RESs are effectively aided by the battery energy storage system (BESS).

When demand is at its highest demand, the stored energy to BESS is released and facilitates the storage of electricity generated from renewable sources.

The rapid response capability battery energy storage systems (BESS) quickly inject or absorb active power to stabilize grid frequency when it deviates from the nominal value, making it more preferred for providing faster frequency response compared to other energy storage technologies (González-Inostroza et al., 2021; Hambissa et al., 2024) in the time scale of seconds or milliseconds.

CONCLUSIONS

The incorporation of renewable energy sources such as wind and solar power into grid networks presents challenges to the overall inertia and frequency regulation. During the imbalances between supply and demand, RESs-dominated power generation lacks the inherent traditional rotational inertia which makes it difficult to maintain grid frequency. The rapid growth of renewable energy, particularly solar power, is having a significant impact on the grid network. On the positive side, the integration of solar and other renewables is helping to minimize greenhouse gas emissions and reliance on fossil fuels. Renewable energy is also increasing grid resilience by diversifying the generation mix and providing distributed decentralized power sources. However, the intermittent and variable nature of solar power presents challenges for grid operators. Increased use of energy storage, advanced forecasting, and greater grid flexibility will be essential to accommodate high levels of solar and other renewable energy. Overall, the growth of solar and other renewables is a net positive for the grid, the environment, and the shift towards a sustainable energy future

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