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A Critical Survey of Transient and Small-Signal Stability Enhancement Techniques in Renewable-Dominated Power Systems

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ABSTRACT

Countries around the world are shifting from traditional power systems dominated by synchronous generators towards renewable-dominated power systems, characterized by high levels of converter-interfaced generators (CIGs). With this shift, a lot of fast power electronic devices will be added to the grid as renewable energy source increases, thus making the system dynamic response increasingly faster and more complex. These future features of the power system create challenges in power system stability and control. To maintain power system stability in the future and achieve a smooth shift in the power system, we need to change from the traditional, synchronous generator-based controls and begin to explore new methods. This paper presents a critical survey on transient and small signal stability of such renewable-dominated power systems. This is achieved by a critical analysis of Transient stability assessment methods, Control-based enhancement and the Impact of inverter-based resources on stability. Constantly increasing number of renewable energy resources such as photovoltaic and wind power plants has a significant impact on the stability of electricity transmission. In this article there are different transient stability assessment methods: TEF, Direct Methods, Time-domain simulation and control-based enhancement techniques: FACTS, PSS, and Wide-Area Measurement Systems that are considered.

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INTRODUCTION

A renewable-dominated power system which is a Clean and efficient new energy generation technologies continues to play a strong role in the context of the global environmental and energy crisis and generates a significant majority of its electricity from inherently variable sources like solar and wind, rather than fossil fuels [1]. While offering sustainability and low emissions, these systems face challenges due to the weather-dependent nature of renewables, a large, sudden disturbance and Insufficient damping. To ensure stability and reliability, they rely on solutions such as energy storage systems, demand response programs, grid-forming converters, enhanced grid infrastructure, and transient and Small-signal stability enhancement techniques.

However, the ensuing large-scale grid integration of renewable power has led to disruptions in grid voltage security and system stability [2] and even to system voltage collapse [3]. Ensuring the stability of the grid connection is currently a top priority in renewable-dominated power system research. Hence it is critical to investigate the influence of renewable sources of energy on transient and small signal stability of power systems and then develop appropriate transient and small-signal stability enhancement techniques to improve transient and small signal stability. It is also very important to note that the rise of renewable energy requires more power

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electronics to connect it to the grid, leading to the development of Power-Electronics-Dominated Power Systems (PEDPS). In this context, transient stability assessment methods: Transfer Energy Function (TEF), direct methods, time-domain simulation; Control-base enhancement: Flexible AC Transmission Systems (FACTS), Power System Stabilizer (PSS), Wide-Area measurement systems and the impact of inverter-based resources on stability are evaluated.

Fundamentals of Power System Stability.

In power systems, according to [4], there are three main groups of power system stability which are, rotor angle stability, frequency stability, and voltage stability, transient and small-signal stability are both aspects of rotor angle stability, which is the ability of synchronous machines in a power system to remain in synchronism after a disturbance. However, transient and small-signal stability both differ fundamentally in the nature of the disturbance and the type of system response they analyze. Transient stability is the ability of a power system to maintain synchronism and regain a stable operating equilibrium after a large, severe disturbance, such as a fault or the loss of a major transmission line. The system exhibits large, non-linear swings in generator rotor angles and other variables.

The main cause of transient instability in a power system is a large, sudden disturbance that creates a severe imbalance between the mechanical input power and electrical output power of synchronous generators. If the disturbance is severe enough or lasts too long, the generator rotors can accelerate or decelerate significantly, causing them to lose synchronism with the rest of the grid. This can lead to a cascade of failures and a widespread power outage.

Factors affecting transient stability

Fault characteristics: The nature of a fault (for example, short circuit, loss of a line) and its position within the power system significantly influence the system's ability to remain stable, also the duration of the fault is critical. Shorter fault clearing times, achieved with high-speed relays and circuit breakers, are crucial for maintaining stability.

System Operating Conditions: The load on generators before a fault occurs impacts their internal voltages and output, affecting the system's ability to maintain synchronism, also the overall loading of the system determines the phase angles between generators' internal voltages, which is a factor in stability. This is but a few of the factors affecting transient stability, more of which can be found in [6]. Small-signal stability is the ability of a power system to maintain synchronism following small, continuous perturbations, such as minor load fluctuations. The analysis determines if the oscillations caused by these disturbances are adequately damped and die out quickly. The system has small, linear electromechanical oscillations around an equilibrium point.

An oscillation is the repetitive, or periodic, variation of a measure over time, typically about a central, stable value called the equilibrium point. Oscillation damping in small-signal stability is the ability of a power system to suppress and reduce low-frequency oscillations following a minor disturbance, helping the system return to a stable operating state. The "small signal" refers to disturbances that are small enough to allow for the linearization of system equations during analysis. More definitions and classifications of the phenomena of power system stability are available in [4,5].

Insufficient damping is the primary cause of small-signal instability, which can be categorized into two main modes:

1. Local modes (1–3 Hz): Involve oscillations of a single generating unit or a small group of units against the rest of the system.
2. Inter-area modes (< 1 Hz): Involve groups of generators in one area swinging against groups in another area, often linked by weak transmission lines

Factors affecting small-signal stability:

System loading and configuration: Operating conditions, like heavy power transfers

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over weak tie lines, can reduce damping and trigger inter-area oscillations.

Control system parameters: The tuning of generator excitation control systems, such as Power System Stabilizers (PSSs), is critical for providing sufficient damping torque.

Integration of renewables: Wind turbines and other non-conventional generation, particularly in microgrids, can significantly alter system inertia and control dynamics, affecting small-signal stability. Location of devices: The placement of generating units or flexible AC transmission system (FACTS) devices can impact how oscillations are damped or stabilized. Mor on factors affecting small signal stability can be found in [7].

Impact of Inverter-Based Resources on Stability

Renewable energy sources (RES) negatively affect power system stability by causing voltage and frequency fluctuations, reducing system inertia, and increasing the Rate of Change of Frequency (RoCoF) during disturbances due to their intermittent nature. Grid operators can mitigate these challenges through advanced grid management techniques, such as deploying Energy Storage Systems (ESS) for buffering power, implementing real-time monitoring and control with smart grid technologies, and utilizing inertia control methods in RES to enhance system stability and reliability.

Recalled from [4], there are three main groups of power system stability which are, rotor angle stability, frequency stability, and voltage stability. Inverter-based resources (IBRs), such as solar and wind power are gaining popularity because of their increasing acceptance, environmental benefits and decreasing costs. However, their integration into power systems can lead to significant impacts on the three main groups of power system stability, such as system inertia and frequency stability and a change in system inertia significantly affects both the system voltage and power angle, primarily by making the grid more vulnerable to instability, which are crucial for maintaining the reliability of the power grid. In traditional power systems, the synchronous generators provide inertia, which helps to stabilize the frequency of the system [84]. However, IBRs do not have this inherent inertia, and their integration can result in a decrease in system inertia, leading to frequency instability. This is because IBRs are typically connected to the grid through power electronics, which can introduce additional control and communication delays that affect the system's response to disturbances. and due to the high penetration of inverter-based resources into the power system which increases the introduction of power converters interface into the system.

Despite the increase in the Variable Renewable Energy Source (VRES) into the power grid which can affect the system stability due to the nonlinear and complex nature of the dynamics of the system, however, when integrated within permissible limits, VRES can enhance system stabilization, the study in [85] reveals a trade-off: while VRES integration improves frequency response, it introduces less coherent and more oscillatory machine behavior, underscoring a limit on VRES penetration for maintaining stability.

A critical VRES penetration threshold of approximately 44 % was identified, beyond which the system faces heightened risks of instability. When such limit is exceeded, it introduces significant challenges, including faster RoCoF, lower frequency nadirs, extended response times, and an elevated risk of protection relay activations, such as UFLS and RoCoF mechanisms. It is imperative to manage VRES integration to prevent instability carefully [85]. To address this, "virtual inertia" is proposed to compensate for the diminishing inertial response of traditional generators [85]. Techniques such as Fast Frequency Response (FFR), battery energy storage systems, and supercapacitors are recommended for further research and integration. This holistic approach is essential for maximizing VRES penetration while ensuring grid stability.

Several studies have examined the challenges posed by the variability of renewable energy sources and declining system inertia on power grids. As VRES penetration rises, the conventional power system's ability to absorb and

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release kinetic energy to stabilize frequency weakens [86]. Given the potential for increased frequency fluctuations and rapid changes in grid conditions, the integration of VRES raises concerns about the grid's resilience in the face of disturbances, such as sudden load changes or generator outages [87], [88] and [89].

Stability Assessment Methods in RES-Dominated System

The assessment of the state of a RES-dominated power system in terms of its stability state is very important, because it forms a base upon which the power system can be improved, because the increased penetration of RES into the power system which is characterized by the traditional use of synchronous machines tends to alter the dynamics of the power system.

There are different methods in which the stability status of a RES-Dominated system can be assessed which we are going to discuss.

Time-domain Simulation

Despite these advances, modeling renewable energy sources, TEF which is Lyapunov function based, still presents challenges. The inherent complexity and speed of power electronic converters, combined with their non-linear behavior, make it difficult to derive accurate and robust analytical TEF. As a result, time-domain simulations remain a crucial tool for validating and refining TEF models for systems with high renewable energy penetration or domination [23].

Time-domain simulation (TDS) for power system transient stability assessment involves modeling the system with differential-algebraic equations (DAEs), simulating the system's response to a fault using numerical integration, and determining stability by analyzing state variables like rotor angles and frequency. Key steps include defining system operational conditions and faults, incorporating detailed dynamic models of conventional generators and renewable energy sources (e.g., wind turbines, solar power), solving the DAEs at each time step, and evaluating system variables against instability criteria [23].

Although one of the limitations of the traditional time-domain simulation is that the stability of the post-fault system is evaluated based on simulated post-fault trajectories with regular simulation periods of about 10-15s, which makes this traditional method rather time-consuming [22]. As a regular tool routinely applied in power systems around the world, the time-domain simulation approach has a long history of application in stability analysis [23].

In terms of the electromechanical transient simulation of power systems, the modified Euler method [24] and fourth-order explicit Runge-Kutta method [25] are widely used because they can better balance the impact of implementation difficulty and accuracy.

Time-domain simulation which is based on Differential-Algebraic Equations (DAEs) is more accurate compared to the Lyapunov based methods because the differential-algebraic equations (DAEs) used in the modelling of the system describe the system's dynamics and constraints, whereas Lyapunov functions are analytical tools used to evaluate the stability of the solutions to such systems.

Time-domain simulations are used to solve differential equations incrementally at each time interval to simulate how a system's variables change over time. Depending on the simulation type used, different dynamics can be captured. The commonly found time-domain simulation approaches for PSS analysis with high-RES integration include EMT, electromechanical, and dynamic simulations. Electromagnetic Transient (EMT) simulation is a time-domain analytic method that solves detailed differential equations to accurately capture instantaneous electrical values. This allows for the study of dynamic events in power systems and fast transients [26].

Electromagnetic Transient (EMT) simulation

Electromagnetic Transient (EMT) simulation models and analyzes rapid, short-duration events (transients) in electrical power systems, such as those caused by switching operations or lightning strikes [26]. These studies are essential for designing stable and resilient power systems, especially with the increasing

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integration of Inverter-Based Resources (IBRs) like solar and wind which introduces complex electromagnetic behaviors that are best studied using EMT simulations to ensure grid stability and proper control.

EMT simulations require high computational power due to their small-time steps and complex component models, leading to the development of parallel processing, cloud computing, and advanced algorithms to improve efficiency and accuracy in analyzing these critical phenomena. Reference [27] presented a practical guideline for EMT modeling to assist in preventing common errors and enhance simulation efficiency, accuracy, and stability. Electromagnetic Transient (EMT) simulation is a time-domain analysis method used to study rapid, short-duration events in electrical systems. The core procedure involves modeling the system, formulating network equations using numerical integration, and solving these equations step-by-step over time. EMT simulation procedure.

1. System modeling

The first step is to represent all system components, such as generators, transformers, transmission lines, and power electronics, with appropriate mathematical models [90].

Lumped-parameter components (R, L, C): These components are typically modeled using their instantaneous current-voltage relationships as seen in equation (1) (2) and (3).

Resistor: $v(t) = Ri(t)$; (1)

Inductor: $v(t) = L\frac{di(t)}{dt}$; (2)

Capacitor: $i(t) = C\frac{dv(t)}{dt}$ (3)

Distributed-parameter components (Transmission Lines): For high-frequency transients, transmission lines and cables are modeled using traveling wave theory, which accounts for the finite propagation speed of electromagnetic waves [90].

The voltage and current at a position x and time t on a lossless lines are given by equation (4) and (5):

$$v(x, t) = v_f(t - \frac{x}{c}) + v_b(t + \frac{x}{c}); \quad (4)$$

$$i(x, t) = \frac{1}{Z_c}[v_f(t - \frac{x}{c}) + v_b(t + \frac{x}{c})] \quad (5)$$

Where v_f and v_b are forward and backward traveling waves, c is the wave propagation speed, and Z_c is the line's characteristic impedance.

Power electronics and non-linear components: These devices are typically represented with ideal switches and controlled sources. Their discrete switching behavior requires special handling within the numerical solution algorithm.

2. Network equation formulation

Using Modified Nodal Analysis (MNA), a system of algebraic-differential equations (DAEs) is created for the entire network based on Kirchhoff's Current Law (KCL).

KCL at a node: The sum of all currents entering a node must equal the sum of all currents leaving it.

$$\sum i_{in} = \sum i_{out} \quad (6)$$

3. Numerical integration (companion model)

To solve the DAEs, numerical integration is applied to convert the differential equations of energy-storing elements (inductors and capacitors) into discrete algebraic equivalents.

The trapezoidal rule is a common method for this purpose.

The trapezoidal integration rule approximates the derivative as:

$$\frac{dx(t)}{dt} \approx \frac{x(t_{n+1}) - x(t_n)}{\Delta t} \quad (7)$$

Using this rule, lumped elements are represented by "companion circuits" valid for a discrete time step (Δt):

Inductor: $v(t_{n+1}) = L\,[\frac{v(t_{n+1}) - v(t_n)}{\Delta t}] \Rightarrow v(t_{n+1}) = \frac{\Delta t}{2L}\, i(t_{n+1}) + [\frac{\Delta t}{2L}\, i(t_n) + v(t_n)]$ (8)

This is equivalent to a resistor $\frac{2L}{\Delta t}$ in parallel with a Norton current source

$$I_h(t_n) = i\,(t_n) + \frac{\Delta t}{2L} v(t_n) \quad (9)$$

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Capacitor: $v(t_{n+1}) = C \left[\frac{i(t_{n+1}) - i(t_n)}{\Delta t}\right] \Rightarrow$ $i(t_{n+1}) = \frac{\Delta t}{2C} v(t_{n+1}) + \left[\frac{\Delta t}{2C} v(t_n) + i(t_n)\right]$ (10)

This is equivalent to a resistor $\frac{\Delta t}{2C}$ in series with a Thevenin voltage source; $V_h(t_n) = v(t_n) + \frac{\Delta t}{2C} i(t_n)$. (11)

4. Matrix assembly and solution

For each time step, the companion circuits are combined with the resistive network to form a large system of linear algebraic equations. This is typically done using matrix stamps for each component [27].

The system can be represented in matrix form:

$Y. v(t_{n+1}) = i_{n+1} + I_h(t_n)$ (12)

Y is the augmented nodal admittance matrix of the network at time t_{n+1}

$v(t_{n+1})$ is the vector of unknown node voltages at t_{n+1}

i_{n+1} is the vector of external source currents injected at t_{n+1}

$I_h(t_n)$ is the history vector containing equivalent currents from inductors and capacitors based on past values at t_n.

This system of equations is solved recursively for each time step Δt, with the solution of one step t_n becoming the "history" for the next (t_{n+1}).

5. Handling non-linear components

Components with non-linear or switching behavior, like power electronic converters, are handled by iterative methods. Compensation Method: This technique treats non-linear devices as a separate part of the circuit with a linear model. A compensation current or voltage source is used to represent the non-linear element, and an iterative process (e.g., Newton-Raphson) is used to find a solution that satisfies both the linear network and the non-linear component model.

6. Time-domain simulation

The time-domain simulation proceeds by repeating steps 4 and 5 for a series of small, fixed time steps, from t = 0 to the desired end time (t_{final}). The results (voltages and currents) are stored and can be used for analysis. The choice of time step is a trade-off between accuracy and computational efficiency [90].

Direct Method

Direct methods for transient stability assessment include the Energy Function Method, which uses Lyapunov theory to compare system energy to critical energy, the Extended Equal Area Criterion (EEAC), an extension of the classical equal area concept, and the Potential Energy Boundary Surface (PEBS) method, which uses the maximum potential energy during a disturbance as a critical energy marker. Other methods, like the Controlling Unstable Equilibrium Point (CUEP) or closest UEP method, also derive from the same stability theory and are designed for fast, real-time stability assessment without the need for extensive numerical integration [90]. Transient stability analysis using the direct method is to first identify the mathematical dynamic model of a system, then derive its Lyapunov function, and finally evaluate the stability criteria directly from the critical energy [90].

Classical TEF and its Limitations

The TEF method is based on the principle of energy balance. A power system's stability can be likened to a ball rolling in a potential energy well. When a disturbance occurs, such as a fault, the system's kinetic energy increases, and its stable equilibrium point (SEP) is shifted. The system can maintain stability if it can convert its excess kinetic energy back into potential energy before reaching an unstable equilibrium point (UEP). The TEF determines if the transient energy gained during a fault is less than the critical energy needed to cause instability, providing a stability margin [90]. Key steps to use TEF for stability assessment:

1. Define the system model

You must first model the power system, including the generators, loads, and network. The TEF method was originally developed for the classical generator model but has been extended

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to incorporate more detailed models. The calculations often use a "center of inertia" (COI) reference frame to simplify the analysis of multimachine systems.

2. Define a Lyapunov function or calculate the transient energy function

Construct a Lyapunov function that represents the system's total transient energy. For traditional systems, this energy includes rotor kinetic energy and potential energy. For systems with renewable energy sources, this must be modified to include energy terms related to the control dynamics and power electronic converters. The total transient energy (V) is composed of several parts, which are Kinetic Energy (V_{KE}): The energy of the generators in motion relative to the COI. Potential Energy (V_{PE}): The energy stored in the system due to the changes in generator angles. Dissipation Energy (V_{diss}): The energy lost in the network's transfer conductance [90].

The general form of the TEF for a multimachine system is given as

$$V = V_{KE} + V_{PE} \quad (13)$$

where: $V_{KE} = \sum_{i=1}^{m} \frac{1}{2} M_i \omega_i^2$ and $V_{PE} = \sum_{I=1}^{m} \int_{\delta_i^s}^{\delta_i} (P_{mi} - P_{ei}) d\delta_i \quad (14)$

Here $M_i$is the inertial constant, ω_i is the rotor speed relative to the COI, P_{mi} is the mechanical power, P_{ei} is the electrical power, and δ_i is the rotor angle of generator i. The integration is performed from the stable equilibrium point (δ_i^s) to the current angle (δ_i).

3. Determine the critical clearing energy

This is the amount of energy that the system can absorb after a fault is cleared, at the unstable equilibrium point (UEP).

First, the post-fault equilibrium points are determined by solving the power flow equations for the system after the fault has been cleared. This identifies the UEP that the system's trajectory is heading towards.

Critical energy (V_{cr}) is calculated as the value of the potential energy function at the UEP.

4. Evaluate the transient energy margin

The transient energy margin (ΔV) is the difference between the critical clearing energy and the transient energy at the time of fault clearing.

$$\Delta V = V_{cr} - V_{clear} \quad (15)$$

Where V_{clear} is the transient energy at the time of fault clearance.

5. Assess stability

If $\Delta V > 0$, the system is considered transiently stable. The transient kinetic energy is less than the potential energy boundary, so the system will return to a stable equilibrium.

If $\Delta V < 0$, the system is considered unstable. The transient energy exceeds the potential energy boundary, and the system is moving toward an unstable operating condition [90].

The magnitude of ΔV gives a quantitative measure of the degree of stability or instability, which is a key advantage of the TEF method.

Applications and extensions

Critical Clearing Time (CCT): The TEF can be used to quickly estimate the maximum time a fault can persist before the system becomes unstable. Online security assessment: The TEF method's speed makes it suitable for online applications, providing a rapid assessment of system security for various contingencies.

Mitigation strategies: Engineers can use TEF to test different corrective actions, such as generation or load changes, to see how they impact the stability margin. Incorporation of advanced models: The TEF has been extended to include more complex system dynamics, such as detailed generator models and the effects of renewable energy sources.

When using Transient Energy Function (TEF) models for power systems that is dominated with renewable energy sources, the main challenge is that these renewable energy sources do not behave like traditional synchronous generators. In [9] it shows the issues in the power system with PV integration, given a case study of Ontario's power system. Therefore, standard TEF approaches must be adopted to account for the unique characteristics of these modern technologies, including power electronics and control systems.

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Challenges with including RES in TEF analysis

Incorporating RES presents several analytical difficulties that make classical TEF methods inadequate: Variable nature of RES: Unlike conventional generators, the output power from wind turbines and solar panels is intermittent and depends on environmental factors. This variability complicates defining a stable operating point for the system.

Power electronic interfaces: RES units are typically connected to the grid via power electronic converters. The dynamic behavior of these converters, including their fast-switching actions and control loops, must be modeled to accurately analyze system stability. Low inertia: Many RES-dominated microgrids have low system inertia compared to traditional power grids. This makes the system more sensitive to disturbances and prone to faster frequency and voltage fluctuations. Non-linear dynamics: The complex interaction between the RES and the grid introduces significant non-linear dynamics that must be considered in the stability analysis.

Advance TEF for RES-Dominated System

The classic TEF is often based on the Equal Area Criterion (EAC) for a single-machine infinite bus (SMIB) system, which can be extended to multimachine systems. The standard EAC or SMIB reduction methods are insufficient for a renewable energy source dominated system, therefore hybrid models are needed that integrate the generator dynamics and the fast converter controls

Methods for including RES in TEF

Researchers have developed several methods to construct Lyapunov and Transient Energy Functions that account for the unique characteristics of RES [90].

1. Fuzzy Lyapunov function method

This approach uses fuzzy logic to handle the uncertainty and non-linearity of power systems with high-RES penetration.
The method computes a fuzzy Lyapunov function based on multiple line integrals and membership functions, which can lead to a less conservative estimate of the stability boundary than traditional quadratic functions [90]. It has been applied to analyze the stability of hybrid multi-frequency systems with wind power.

2. Sum-of-Squares (SOS) programming

SOS programming is a mathematical technique used to prove the non-negativity of a polynomial by decomposing it into a sum of squared polynomials. This method can be used to construct a Lyapunov function for complex non-linear systems, including those with wind turbines and HVDC dynamics [90]. It provides a more accurate estimation of the system's region of attraction compared to traditional methods.

3. Power-converter-specific Lyapunov functions

Since most RES connect via power electronic converters, Lyapunov functions have been developed specifically for these devices.
For example, researchers have used the Lyapunov direct method to design current controllers for renewable sources connected to microgrids. Other studies have focused on the stability analysis of grid-connected Voltage Source Converters (VSCs), which are critical components for RES integration.

4. Singular perturbation theory

Microgrids often contain elements with dynamics spanning different timescales, making them "multi-time scale systems". Singular perturbation theory can be used to reduce the model order by separating the system into "fast" and "slow" subsystems. A Lyapunov function can then be applied to the reduced-order model, simplifying the large-signal stability analysis and improving computational efficiency.

5. Lyapunov exponent-based assessment

This method uses Maximum Lyapunov Exponents (MLE) to assess the stability of dynamic systems with RES.
The model-based approach uses the system's differential equations, while a model-free approach can analyze time-series data from the system. The sign of the MLE indicates stability

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(negative for stable, positive for unstable), and the approach can be applied to complex non-linear systems with high-RES penetration.

6. Lyapunov optimization

Lyapunov optimization can be used for the energy management of Hybrid Renewable Energy Systems (HRES) in real-time. It manages energy distribution by defining a "virtual energy queue" and minimizing a "drift-plus-penalty" function to maintain queue stability and control costs.

This method ensures stability while simultaneously optimizing energy flows from different sources.

Calculation steps using a simplified RES model

Here is a simplified example of how to approach the calculation of a Lyapunov function for a power system with an inverter-interfaced RES.

Step 1: Develop the system model

Create a non-linear state-space model that represents the dynamics of the system, including both conventional synchronous generators (if any) and the RES. The model for the inverter-based RES must account for the dynamics of the converter, its filters, and its controllers. For example, a common state-space representation for a Voltage Source Converter (VSC) is:

$$\dot{x} = f(x) \tag{16}$$

where x is the state vector including inverter currents, voltages, and potentially the DC bus voltage.

Step 2: Define a candidate Lyapunov function

Choose a candidate function, V(x), that resembles the system's energy. This function must be positive definite, meaning V(x) > 0 for $x \neq x_{eq}$ and $V(x_{eq}) = 0$, where x_{eq} is the equilibrium point. For a simple system, a quadratic form can be used: $V(x) = x^T P x$, where P is a positive definite matrix. For more complex, non-linear systems, an energy-based function that accounts for the kinetic and potential energy of the system is often constructed [90].

Step 3: Calculate the time derivative of the Lyapunov function

Use the system's state-space model to find the time derivative of V(x), which is

$$\dot{V}(x) = \frac{\partial V}{\partial x}\dot{x}. \tag{17}$$

The derivative must be negative definite or negative semi-definite, meaning

$$\dot{V}(x) \leq 0 \text{ for } x \neq x_{eq} \tag{18}$$

Step 4: Incorporate RES dynamics and controls

Adjust the model and the Lyapunov function to include the specific control strategies of the RES. For example, if the inverter uses a droop controller, the dynamics of the controller must be included in the state-space model and reflected in the calculation of $\dot{V}(x)$ [90]. The goal is to ensure that the chosen control laws make the system's Lyapunov function decrease over time, leading to a stable state.

Step 5: Determine the Region of Attraction (ROA)

The size and shape of the ROA, where the system is guaranteed to be stable, can be estimated by analyzing the Lyapunov function. For non-linear systems with RES, finding an accurate and non-conservative ROA is an active area of research. Advanced methods like Sum-of-Squares (SOS) programming can help enlarge the estimated ROA. Furthermore [10,11] discusses some stability indicators in power system. Below is the flow chat for the procedure of establishing a Lyapunov function for the power system.

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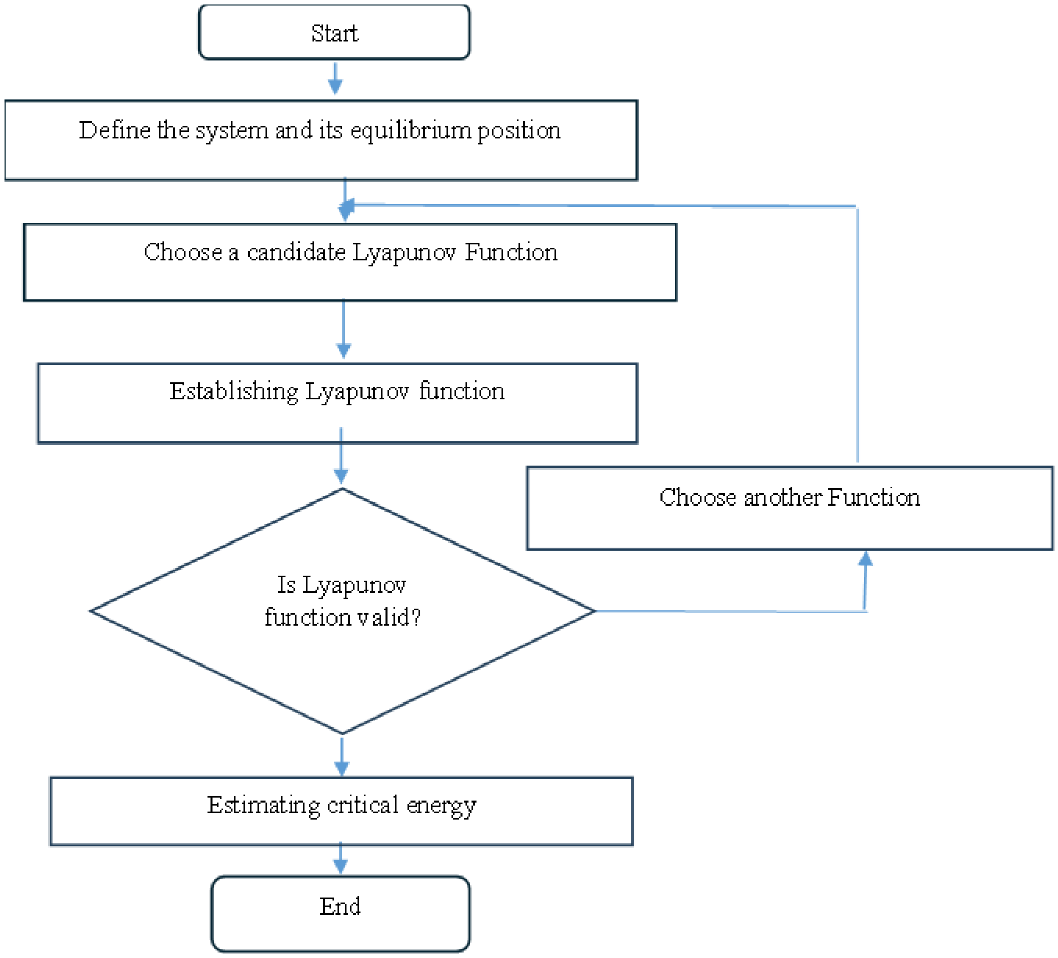

Figure 1.1: Flowchart

Hybrid and Data-Driven Methods

Recent research on using the direct method for transient stability assessment (TSA) has focused on combining it with machine learning techniques, addressing modern power system complexities, and improving real-time performance. These hybrid approaches offer significant advantages over traditional time-domain simulations and pure direct methods, which can struggle with large-scale power systems and renewable energy integration.

Traditional direct methods, such as the Lyapunov-based method and Transient Energy Function (TEF), analyze system stability without performing computationally intensive time-domain simulations. They typically compare the system's total energy with a critical energy value to determine stability.

At present, Nonsynchronous Energy Sources (NESs) such as renewable power generation, flexible AC transmission systems (FACTS), High Voltage Direct Current (HVDC) transmission systems, energy storage devices, and Direct Current (DC) microgrids are increasingly widely employed in power systems [12–16]. Under the considerable renewable energy source penetration, the system dynamic characteristics can potentially deviate from those of the traditional AC power system. To contain system transient instability issues such as short-term frequency variations and voltage fluctuations

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is a major challenge for system operators [17, 18]. In addition, in Europe and America, with the development of power electronics-dominated power systems (renewable energy sources), it inevitably brings some problems to the system, such as the complexity of design in some devices, difficulty in setting the parameter of relay protection [19], difficulty in system stability and limit analysis [20], harmonic suppression and reactive power compensation [21], and so on. By virtue of fast-switched power electronics, nonsynchronous energy sources possess an enhanced controllability of the system and can potentially improve the transmission performance of the system.

We will not say much here as we have already seen the dynamics involved in determining the criterion required to assess the transient stability of a system which is to identify the mathematical dynamic model of a system, to derive its Lyapunov function, and to evaluate the stability criteria directly from the critical energy.

Control-based enhancement Techniques

The worldwide transition towards renewable energy systems with high shares of converter-interfaced generators (CIGs) such as wind and solar power plants, is accelerating at a rapid pace. While some countries have already reached solar and/or wind power capacity beyond their own electricity demand [28], [29], [30], others like Ireland are targeting a 100% renewable-based electricity system in the future [31]. The ongoing energy transition is, however, not an easy task. Several technical challenges must still be overcome before these new generation technologies are widely deployed in power systems. One of the main hindrances to their massive deployment is the inherent dynamic behavior of CIGs and its significant differences with conventional generation facilities. Lack of inertial response [3], [32], [33], [34], low short circuit current capability [35],[36],[37], [38], and fast dynamics within the electromagnetic timescale [39], [40], are among the key features of CIGs that will impact the stability of electricity systems in the future.

Increased levels of CIGs weaken power systems by decreasing the short circuit levels and rotational inertia in the grid. Operational and stability challenges in weak low-inertia systems can manifest themselves in several ways. In steady state, low short circuit levels in busbars result in high values of $\frac{dV}{dP}$ and $\frac{dV}{dQ}$, which in turn means that small disturbances in power flows can significantly change the network voltages [35], [38].

From a stability perspective, weak systems may experience extremely depressed voltages over wide network areas, which may challenge the voltage recovery after short-circuits. Severe voltage dips may also speed up the rotors of the nearby synchronous generators (SGs), which may lead to their loss of synchronism. After major power imbalances, low inertia systems may exhibit steeper rates of change of frequency (RoCoF) and hence larger frequency excursions [32]. This may result in situations in which traditional protection schemes become too slow for preventing large frequency deviations which could lead to load shedding [34]. New stability phenomena such as converter-driven instability and electric resonance instability are also most likely to arise under weak grid conditions [39]. However, unstable interactions between the grid with CIG controls and with the controls of other nearby power electronics-based devices are also to be expected in situations with high levels of converters [41].

Traditionally Improving stability often involves reducing fault clearing time with high-speed breakers, lowering system reactance, increasing system voltage, and improving generator inertia. While in a system where there is high penetration of renewable energy source of power, control-based techniques for enhancing transient and small signal stability in renewable-dominated power systems primarily involve advanced controller designs for converters and grid-forming inverters, including Power System Stabilizers (PSSs) integrated with advanced algorithms, Flexible AC Transmission Systems (FACTS), and customized control strategies for renewable energy system (RES) that mimic synchronous machine behavior, such as Virtual

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Synchronous Generators (VSGs) and the likes. These methods aim to improve power oscillations, critical clearing times, and the system overall ability to remain synchronized after disturbances by controlling voltage, frequency and damping power.

In this paper we will focus on some of the control-based enhancement techniques which include Fast AC Transmission System (FACTS), Power System Stabilizer (PSS) and Wide-Area Measurement Systems.

Flexible AC Transmission Systems (FACTS)

Flexible AC Transmission Systems (FACTS) devices are key enhancement techniques for both transient and small-signal stability in renewable-dominated power systems, improving voltage control, power flow, and damping power oscillations. Their role is increasingly vital due to the low inertia of renewables and the unique challenges presented by grid-following and grid-forming converters. FACTS devices, such as STATCOMs and UPFCs, can inject or absorb reactive power, modulate voltage, and control power flow in real-time, which helps to stabilize the grid during faults and disturbances.

There is comprehensive work done in [42] on FACTS device in a renewable energy dominated power system, where the various FACTS devices are classified based on how they are connected in a power system and the type of power electronics they are made up of, where we have the first and second generation of FACTS devices and how these devices mitigate against disturbances or instabilities in the power system.

Wind energy, as the most significant variable renewable energy source, has prompted extensive research into its impact on the stability of electrical grids, especially when integrated in large amounts. A variety of wind energy conversion systems (WECS), including Permanent Magnet Synchronous Generator (PMSG) based WECS, Doubly-Fed Induction Generator (DFIG), and Squirrel-Cage Induction Generator (SCIG), have been the focus of many studies. The SCIG-WECS tends to draw reactive power from the grid rather than supply it, necessitating using a capacitor bank at its stator terminals for reactive power support. On the other hand, DFIG-WECS can supply and absorb reactive power, which aids in maintaining the voltage at the grid's connection points [43]. Consequently, SCIG-WECS are more likely to negatively impact grid voltage stability than DFIG-WECS.

Still in the research work in [43] static and dynamic voltage stability analyses were conducted on grid-connected wind farms that included FACTS (Flexible AC Transmission Systems) devices. The static analysis utilized methods like power flow, PV curve analysis, and QV modal analysis to assess the voltage stability of the IEEE 14-bus test system [43]. Dynamic analysis was then performed to evaluate the performance of SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator) under normal and contingency conditions [43]. The findings revealed that both SVC and STATCOM contribute to improved steady-state voltage stability and increased network load-ability margins. However, STATCOM was more effective in enhancing dynamic voltage stability [43].

Additionally, in [44] the study focused on the stability improvement of power systems integrated with different wind energy conversion systems: SCIG-WECS (Squirrel-Cage Induction Generator), DFIG-WECS (Doubly-Fed Induction Generator), and a combined wind farm incorporating both SCIG and DFIG WECS. In this scenario, the SCIG-WECS and DFIG-WECS were equipped with an SSSC (Static Synchronous Series Compensator) controller, while the combined wind farm operated without any FACTS device [44]. The Voltage Stability Index (VSI) was used to assess voltage stability in each case. The results indicated that while the SSSC controller enhanced the performance of the SCIG-WECS and DFIG-WECS setups, the combined wind farm without the SSSC controller exhibited the best overall performance [44]. It is important to note that this study only considered the SSSC controller and did not explore the impact of other FACTS.

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Further advancements in analytical tools and methodologies have been made to study voltage stability, such as continuation power flow and eigenvalue analysis. For instance, in [45], these methods were applied to evaluate the voltage stability of Kerala's 220KV, 26-bus grid system, which includes wind power integration and the application of SVC.
These studies collectively demonstrate that STATCOM generally outperforms SVC in enhancing voltage stability in power systems integrated with wind energy conversion systems [45].

Numerous studies have examined the impact of Solar Photovoltaic (SPV) integration on the voltage stability of power systems, as referenced in publications [46 – 54]. In one such study [48], researchers analyzed the influence of SPV integration on the dynamic voltage stability of a power system, using the Dominion Virginia Power system as a model. They explored various PV penetration scenarios and found that high SPV penetration can significantly affect the dynamic voltage stability of a power grid.

In a novel approach presented in [50], researchers introduced the concept of using an SPV inverter as a Static Synchronous Compensator (STATCOM), termed PV-STATCOM. This device enhances power transmission limits both during the day and at night [50]. The study conducted transient stability analysis using a realistic single-machine infinite-bus power system model, where the PV-STATCOM was located at the midpoint of the system. The analysis, performed using EMTDC/PSCAD software, indicated that PV-STATCOM could substantially improve stable power transmission limits, irrespective of whether it was the day (with high active power generation) or night.

Further research in [55] focused on applying PV-STATCOM equipped with voltage and damping controllers to increase the power transfer capacity of transmission lines. This study also included harmonic analysis, finding that situating PV-STATCOM at the center of a transmission line effectively enhances system stability by reducing Total Harmonic Distortion (THD) during fault conditions.

Another significant study [56] explored optimizing additional reactive and active power control strategies in SPV plants. It used the particle swarm optimization (PSO) technique to tune the real and reactive power support, considering the rates of change in frequency, voltage, and voltage phase angle. This research concluded that while active and reactive power support from SPVs can adversely affect grid stability post-fault, the PSO-based tuning of SPV parameters could counteract these negative impacts. FACTS devices effectively remedy power quality issues by integrating high-power renewable energy sources with conventional power grids. Their rapid compensation of active and reactive power positions them as a viable replacement for earlier methods. These devices contribute to maintaining voltage stability and managing power flow control.

How FACTS Improve Stability

Transient Stability

Voltage Support: FACTS devices can provide rapid voltage regulation, which helps to maintain system voltage during faults and prevents voltage collapse, a common cause of transient instability[57]. Power Flow Control: By managing power flow, FACTS can reroute power around weak parts of the grid, reducing the severity of disturbances and preventing generators from losing synchronism after a fault.
Dynamic Braking: Some FACTS devices can provide dynamic braking, which quickly absorbs excess energy and helps to slow down accelerating rotors, thus improving the critical clearing time (CCT). In terms of economic implications FACTS is capital intensive due to the its maintenance cost and the power electronic based nature.

Power System Stabilizer (PSS)

The transition of the energy sector towards distributed power systems with large share of renewable inverter connected generation and less synchronous machines (SM) with electro-mechanical inertia demands novel concepts and

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approaches for stabilizing low frequency power oscillations using power system stabilizers (PSS) [57]. The increased share of economically efficient renewable generation dictates larger presence of DC generation in the power system. Although quite efficient at a micro and nano grid level, the DC networks implementation has some major efficiency limitations on a macro and super grid level. Thus, it is expected that the traditional three phase AC networks will keep their prevailing role on a bulk power system level.

Different solar, wind and hydro generation units connected via power electronic inverters are already significant enough to influence the power system stability [58], and hence the need for control-based enhancement techniques which also include the PSS functionality of the present-day generation which has the functions to mimic the traditional synchronous machine is necessary and plays a vital role for the power system stability to mitigate instability in the power system. Thus, an adequate alternative of the PSS functionality for the future system architecture needs to be found.

Recent research on Power System Stabilizers (PSSs) for renewable-dominated systems focuses on adapting and implementing PSS functions within inverter-based resources (IBRs), as traditional PSSs are not directly applicable to IBRs like wind turbines and solar PVs. Studies explore adaptive and intelligent tuning methods for PSS settings, often utilizing AI-based approaches like Long Short-Term Memory (LSTM) or fuzzy logic, to handle the increased dynamic complexity and declining inertia caused by IBRs.

In recent times, researchers have leveraged modern technologies and methodologies to assess the robustness of their PSS. Among the prevalent techniques are rapid control prototyping (RCP), hardware-in-the-loop (HIL), and software-in-the-loop (SIL). As electrical power networks have grown increasingly complex over the past few decades, there has been a corresponding evolution in verification methodologies and related test tools. Compared to older techniques, real-time technology now offers benefits like faster operations, higher computation powers, high-speed processing, and improved performance. Because experimental study is more tractable and reproducible than simulation results, HIL-based verification approach enables researchers to employ it to test their developed PSS model [59]

This article [60] proposes a Marine Predator Algorithm (MPA) approach to optimize PSS parameters to enhance small signal stability in power systems. The MPA stands out for its robustness and adaptability across a range of optimization problems. MPA has demonstrated its success in various domains, including blade shape optimization of Savonius wind turbines [61], parameter estimation of photovoltaic systems, and energy efficiency optimization in buildings with solar panel systems [62]. Furthermore, it has been effectively applied to pavement maintenance and rehabilitation planning [63] and optimal allocation of active and reactive power resources in power distribution networks [64]. These diverse applications highlight the versatility of the MPA in addressing both engineering challenges and resource optimization problems, establishing its potential for broader applications. In terms of economic implications PSS are not expensive as compared to the FACTS due to it primary function of damping low frequency oscillations.

Wide-Area Measurement Systems (WAMS)

Wide-Area Measurement Systems (WAMS) serve as a crucial control base enhancement technique for power systems with high renewable energy penetration. By providing real-time, synchronized data from across the grid, WAMS addresses the key stability challenges posed by the intermittent nature of renewables like solar and wind. With the emergence of high renewable energy penetration in the power system to sustain power system stability in future power systems and achieve a seamless transition, we need to shift from the current traditional synchronous machine-based control practices and begin to explore new methods. A promising technology to overcome control complexities and underlying stability issues in future low-inertia power systems are wide area measurement systems (WAMS) [65]. Within this technology,

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control is no longer based on purely localized tasks but rather a set of coordinated actions across wide areas in which interplant communication plays a key role.

The successful operation of existing power systems relies on a huge array of control loops responsible for regulating key system quantities. The control organization utilizes architectures in which three levels can be distinguished: generation, transmission, and distribution. Depending on where the decisions are made as well as on the number of measurements that are utilized to make the control decisions [68], these control strategies can be roughly categorized as decentralized, centralized, distributed, and hierarchical [68], [69]. These factors also define the computational and communicational requirements of each strategy [66], [67]. The detailed categorization of the decentralized, centralized, distributed, and hierarchical can be found in [65].

In [65] it also states the limitations of the present-day use of supervisory control and data acquisition (SCADA) as a measurement and communication system. SCADA usually entails one (or more) central host computer linked to several remote terminal units (RTUs) and/or programmable logic controllers (PLCs) located at key network busbars [70], [71], [72]. RTUs are primarily stand-alone data acquisition and control units [65]. Even though SCADA's update period can range between 1 and 3 seconds, measurements from the RTUs are not synchronized with each other and include a deadband to limit data transfer. Hence, high transmission delays and low precision are typical characteristics of SCADA [70], [71]. In terms of control, the update period of SCADA limits its application for fast and complex control actions, especially during contingencies [73], since real-time dynamics cannot be observed.

An alternative technology to RTUs is phasor measurement units (PMUs). A PMU is a device used to estimate the phase and magnitude of voltages, currents, and local frequency of the network busbar or line, reconstructing phasor quantities with synchronized time stamps, thus allowing synchronized real-time measurements of multiple remote points on the grid. Compared to traditional RTUs, PMUs are more accurate and faster (making up to 60 measurements per second), and have lower communication delays [74], [75]. The wide deployment of PMUs in power systems has resulted in the development of wide-area measurement systems (WAMS). WAMS can be used for estimating the state of a power system through synchronized system-wide phasor signals in combination with conventional measurements. The information measured by the PMUs - including the synchronized time stamps, is sent to a phasor data concentrator (PDC) through an Ethernet connection or a similar communication network. The PDC receives, parses, and sorts all the received data. Due to the large amount of information exchange, PDCs require high computational capacity and wideband communication, constraining the number of PMUs associated with each PDC hardware [76].

Despite being considerably faster than SCADA systems, when using WAMS-based control systems for real-time applications, communication delays and/or failures may lead to instabilities or system blackouts. In fact, the time-delay caused by transmission of global signals is one of the key factors influencing system stability and damping performance [77], [78], [79]. Usually, time delays related to communications in WAMS vary from tens to several hundred milliseconds [77], [78], [80]. The exact value depends on the type of communication link, communication network length, communication, network bandwidth load, and transmission protocol, among other factors [78], [80]. Accordingly, time delays should be properly considered when designing control schemes [79]. Although time-delays have traditionally been treated as constant [81], this may not always reflect the reality, and such adoption impacts the communication latency of WAMS-based control systems [81]. In fact, [81], [82], [83] considered time-delays as a stochastic phenomenon, better capturing the effects of real WAMS delays.

In terms of economic implications WAMS also has significant financial implications because of the hard wares and infrastructure,

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several technical and operational challenges related to communication and data management.

Below is a tabular comparison of the above enhancement techniques in the power system.

Table 1: A comparison of the different Stability enhancement Techniques

	FACTS	PSS	WAMS
1	It mainly meant for voltage regulation both for traditional power system and system dominated by renewable energy source	Applicable where synchronous generators are involved	It is a modern system for power system monitoring for both traditional power system and system dominated by renewable energy source
2	For improvement of control, stability, and power transfer capability in transmission system	For damping of low frequency generator oscillation	Its major function is to enhance situational awareness, stability, and reliability by providing real-time, synchronized data from across a large geographical area.
3	It is a distinct hardware device, for example is a STATCOM	It is primarily a control function not a distinct hardware device	It is primarily a control function and a system of application not a single hardware device
4	In terms of cost implication, it is expensive.	In terms of cost implication, it is less expensive compared to FACTS.	In terms of cost implication, it is expensive because of it complexity.

Research Gap

While there is so much literature on transient and small-signal stability assessment methods, control-based enhancement techniques, and the impact of inverter-based resources on power system stability, there is a clear lack of integrated approaches that address the complexity of the system in as much as there are systems that addresses the unique challenges posed by high renewable penetration, such as low system inertia, converter-dominated dynamics, and fast-changing system behavior simultaneously. Furthermore, the development of comprehensive, adaptive, and scalable stability assessment and enhancement strategies tailored to renewable-dominated, complexity of the systems remains an open research area.

CONCLUSION

In conclusion, there is indeed a trend in the vast penetration of renewable energy sources into the power system, which is raising the development of the system by the introduction of systems like the PV-STATCOM, WAMS-based PSS that will enhance the stability of the system irrespective of the high penetration of renewable sources of energy. Also, stability assessment is moving beyond the classical models to embrace

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hybrid and advanced Lyapunov methods to handle CIG dynamics, while enhancement is shifting from external devices (FACT) to inverter-embedded controls (VSG, PV-STATCOM) coordinated over wide areas. Further work must address the issues of complexity in the addition of systems to enhance stability of the power system.

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REFERENCES

[1] Qi Liu; Jiahui Wu; Haiyun Wang; Analysis of DFIG Interval Oscillation Based on Second Order Sliding Film Damping Control MDPI March 202316(7):3091 DOI:10.3390/en16073091

[2]. Ning, L.; Zhao, G.; Du, L.; Wang, S.; Chen, Y. Multi-Domain Optimal Scheduling of Wind Power Systems Based on Voltage Stability Constraints. In Proceedings of the 2020 International Conference on Artificial Intelligence and Electromechanical Automation (AIEA), Tianjin, China, 26–28 June 2020; pp. 1373–1384

[3]. Kunju muhammed, L.; Pal, B.; Oates, C.; Dyke, K. Electrical oscillations in wind farm systems: Analysis and insight based ondetailed modeling. IEEE Trans Sustain. Energy 2016,1, 51–62

[4]. Kundur, P.; Paserba, J.; Ajjarapu, V.; Andersson, G.; Bose, A.; Canizares, C.; Hatziargyriou, N.; Hill, D.; Stankovic, A.; Taylor, C.; et al. Definition and classification of power system stability. IEEE Trans. Power Syst. 2004, 19, 1387–1401. [Google Scholar] [CrossRef]

[5]. Kundur, P. Power System Stability and Control; McGraw-Hill: New York, NY, USA, 1994; ISBN 0070635153. [Google Scholar]

[6]. Tao Liu; Peipeng, Zhou; Siqi Lv; Bin Han; Zutao Xiang; Jingyan Ma Analyses of Factors Affecting Transient Synchronous Stability of Grid-connected Systems with Full-power Converters at the 9th International Conference on Power and Renewable Energy (ICPRE) [IEEE Xplore]

[7]. Omar Mrehel; Kihaled Ghambirlou; Anas Ahhnhli; Abdulaziz Abdulurasoul; Factors affecting Small Signal Stability in Two Area System July 2018 Conference: 5th International Conference on Green Energy and Environmental Engineering (GEEE-2018)

[8]. Vittal, V., et al.: Derivation of stability limits using analytical sensitivity of the transient energy margin. IEEE Trans. Power Syst. 4(4), 1363–1372 (1989) [Google Scholar]

[9]. Nasib Khadka; Kathmandu University; Ramesh Paudel; Brijesh Adhikary; Kathmandu University; Aayush Bista; Kathmandu University: Transient Stability in Renewable Energy Penetrated Power Systems: A Review December 2020 Conference: RESSD 2020 International Conference on Role of Energy for Sustainable Social Development in 'New Normal' Era. At: Virtual

[10]. D. Tools, "TSAT model manual. Powertech Labs Inc," British Columbia, Canada, pp. 105-107, 2011. [17] L. G. Meegahapola, T. Littler, and D. Flynn, "Decoupled-DFIG fault ride-through strategy for enhanced stability performance during grid faults," IEEE Transactions on Sustainable Energy, vol. 1, no. 3, pp. 152

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E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

[11]. L. G. Meegahapola, T. Littler, and D. Flynn, “Decoupled-DFIG fault ride-through strategy for enhanced stability performance during grid faults,” IEEE Transactions on Sustainable Energy, vol. 1, no. 3, pp. 152-162, 2010
[12]. Hu J., Wang B., Wang W. et al., On small signal dynamic behavior of DFIG-based wind turbines during riding through symmetrical faults in weak AC grid, IEEE Transactions on Energy Conversion. (2017) 2017, no. 99. Google Scholar
[13]. Kalcon G. O., Adam G. P., Anaya-Lara O., Lo S., and Uhlen K., Small-signal stability analysis of multi-terminal VSC-based DC transmission systems, IEEE Transactions on Power Systems. (2012) 27, no. 4, 1818–1830, https://doi.org/10.1109/tpwrs.2012.2190531, 2-s2.0-84867983195. Google Scholar
[14]. Tang G., Xu Z., and Zhou Y., Impacts of three MMC-HVDC configurations on AC system stability under DC line faults, IEEE Transactions on Power Systems. (2014) 29, no. 6, 3030–3040, https://doi.org/10.1109/tpwrs.2014.2315666, 2-s2.0-84908376250. Google Scholar
[15]. Hatziargyriou N., Asano H., Iravani R., and Marnay C., Microgrids, IEEE Power and Energy Magazine. (2007) 5, no. 4, 78–94, https://doi.org/10.1109/mpae.2007.376583, 2-s2.0-34547475943. Google Scholar
[16]. Zhang Y. and Xie L., A transient stability assessment framework in power electronic-interfaced distribution systems, IEEE Transactions on Power Systems. (2016) 31, no. 6, 5106–5114, https://doi.org/10.1109/tpwrs.2016.2531745, 2-s2.0-84959275788. Google Scholar
[17]. Yuan X., Cheng S., and Jiabing H. U., Multi-time scale voltage and power angle dynamics in power electronics dominated large power systems, Proceedings of the CSEE. (2016) 36, no. 19. Google Scholar
[18]. Rowe C. N., Summers T. J., and Betz R. E., Arctan power frequency droop for power electronics dominated microgrids, Australian Journal of Electrical & Electronics Engineering. (2013) 10, no. 2, 157–165, https://doi.org/10.7158/e12-012.2013.10.2, 2-s2.0-84879953040. Google Scholar
[19]. Hu J., Huang Y., Wang D., Yuan H., and Yuan X., Modeling of grid-connected DFIG-based wind turbines for DC-link voltage stability analysis, IEEE Transactions on Sustainable Energy. (2015) 6, no. 4, 1325–1336, https://doi.org/10.1109/tste.2015.2432062, 2-s2.0-84960810112. Google Scholar
[20]. Wu T. F., Special issue on power electronics in DC distribution systems, IEEE Transactions on Power Electronics. (2013) 28, no. 4, 1507–1508, https://doi.org/10.1109/tpel.2012.2219111, 2-s2.0-84894342360. Google Scholar
[21]. Song Y. and Blaabjerg F., Wide frequency band active damping strategy for DFIG system high frequency resonance, IEEE Transactions on Energy Conversion. (2016) 31, no. 4, 1665–1675, https://doi.org/10.1109/tec.2016.2591779, 2-s2.0-85003036792. Google Scholar
[22]. Transient Stability Analysis of Large-scale Power Systems: A Survey Qing-Hua Wu, Life Fellow, IEEE, Fellow, CSEE, Yuqing Lin, Chao Hong, Member, CSEE, Yinsheng Su, Member, CSEE, Tianhao Wen, and Yang Liu, Member, IEEE, Member, CSEE
[23]. B. Stott, “Power system dynamic response calculations,” Proceedings of the IEEE, vol. 67, no. 2, pp. 219–241, Feb. 1979.

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E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

[24]. P. M. Anderson and A. A. Fouad, Power System Control and Stability. Oxford: John Wiley & Sons, 2008.

[25]. E. Hairer and G. Wanner, Solving ordinary differential equations II, 2nd ed., Berlin: Springer, 1996.

[26]. Power System Stability With High Penetration of Renewable Energy Sources: Challenges, Assessment, and Mitigation Strategies JANA SHEIKH ALI, YAZAN QIBLAWEY, (Member, IEEE), ABDULRAHMAN ALASSI, (Senior Member, IEEE), AHMED M. MASSOUD, (Senior Member, IEEE), S. M. MUYEEN, (Fellow, IEEE), AND HAITHAM ABU-RUB, (Fellow, IEEE) This work was supported in part by the Second Cycle of ARG from Qatar Research, Development and Innovation (QRDI) Council, Qatar, under Grant ARG02-0416-240192; in part by the Open Access funding is provided by the Qatar National Library; and in part by Iberdrola S. A. as part of its Innovation Department Research Studies

[27]. X. Ma and X.-P. Zhang, ''Basics of electromagnetic transients: Underlying mathematics,'' IEEE Electrific. Mag., vol. 11, no. 4, pp. 8–19, Dec. 2023, doi: 10.1109/MELE.2023.3320485

[28]. J. Taouba, M. Uros, and G. Dominic. (2018). New Options for Existing System Services and Needs for New System Services. Accessed: Feb. 21, 2021. [Online]. Available: https://www.h2020 migrate.eu/_Resources/Persistent/5c5beff0d5bef78799253aae9b19f50a9cb6eb9f/D3.2Localcontrolandsimulationtools forlargetransmission systems.pdf

[29]. G. Denis, T. Prevost, M.-S. Debry, F. Xavier, X. Guillaud, and A. Menze, ''The migrate project: The challenges of operating a transmission grid with only inverter-based generation. A grid-forming control improvement with transient current-limiting control,' IET Renew. Power Gener., vol. 12, no. 5, pp. 523–529, Apr. 2018.

[30]. F. Milano, F. Dorfler, G. Hug, D. J. Hill, and G. Verbic, Foundations and challenges of low-inertia systems (invited paper),'' in Proc. Power Syst. Comput. Conf. (PSCC), Jun. 2018, pp. 1–25.

[31]. X. Zhao, P. Guhathakurta, and D. Flynn. (2019). New Options in System Operations. Accessed: Feb. 18, 2021. [Online]. Available: https://www. h2020-migrate.eu/_Resources/Persistent/5d0f8339650bcf53cd24a30065 56daa1da66cb42/D3.4%20-%20New%20Options%20in%20Syste m %20Operations.pdf

[32]. P. Tielens and D. Van Hertem, "The relevance of inertia in power systems,' Renew. Sustain. Energy Rev., vol. 55, pp. 999–1009, Mar. 2016.

[33]. B. Kroposki, B. Johnson, Y. Zhang, V. Gevorgian, P. Denholm, B.-M. Hodge, and B. Hannegan, ''Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy,'' IEEE Power Energy Mag., vol. 15, no. 2, pp. 61–73, Mar. 2017.

[34]. A. Ulbig, T. S. Borsche, and G. Andersson, ''Impact of low rotational inertia on power system stability and operation,'' in Proc. 19th IFAC World Congr., 2014, pp. 1–12.

[35]. Integrating Inverter Based Resources into Weak Power Systems Reliability Guideline, North Amer. Electr. Rel. Corp. (NERC), Atlanta, GA, USA, Jun. 2017.

[36]. Short-Circuit Modeling and System Strength White Paper, North Amer. Electr. Rel. Corp. (NERC), Atlanta, GA, Feb. 2017.

[37]. IEEE/NERC Task Force on Short-Circuit and System Performance Impact of Inverter Based Generation, Impact of Inverter Based Generation on Bulk Power System Dynamics and Short-Circuit Performance, IEEE Power &

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Energy Soc., Piscataway, NJ, USA, 2018.

[38]. AEMO. Fact Sheet: System Strength. Accessed: Apr. 13, 2021. [Online]. Available: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/2016/AEMO-Fact-Sheet-System-Strengt h-Final-20.pdf

[39]. N. Hatziargyriou, J. Milanovic, and C. Rahmann, ‘‘Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies,’’ IEEE Trans. Power Syst., vol. 11, pp. 2108–2117, 2020.

[40]. J. Vega-Herrera, C. A. Rahmann, F. Valencia, and K. Strunz, ‘‘Analysis and application of quasi-static and dynamic phasor calculus for stability assessment of integrated power electric and electronic systems,’’ IEEE Trans. Power Syst., vol. 36, no. 3, pp. 1750–1760, May 2020.

[41]. N. Hatziargyriou, J. Milanovic, C. Rahmann, V. Ajjarapu, C. Canizares, I. Erlich, D. Hill, I. Hiskens, I. Kamwa, B. Pal, P. Pourbeik, J. SanchezGasca, A. Stankovic, T. Van Cutsem, V. Vittal, and C. Vournas, ‘‘Definition and classification of power system stability–revisited & extended,’’ IEEE Trans. Power Syst., vol. 36, no. 4, pp. 3271–3281, Jul. 2021, doi: 10.1109/TPWRS.2020.3041774

[42]. A comprehensive review of FACTS devices in modern power systems: Addressing power quality, optimal placement, and stability with renewable energy penetration
Author links open overlay panelBan H. Alajrash [a], Mohamed Salem [a], Mahmood Swadi [b], Tomonobu Senjyu [c], Mohamad Kamarol [a], Saad Motahhir [d]
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[43]. K.Z. Heetun, S.H. Abdel Aleem, A.F. Zobaa Voltage stability analysis of grid-connected wind farms with FACTS: Static and dynamic analysis Energy Policy Res., vol. 3 (1) (2016), pp. 1-12 Google Scholar

[44]. A. Rashad, S. Kamel, F. Jurado Stability improvement of power systems connected with developed wind farms using SSSC controller Ain Shams Eng. J., vol. 9 (4) (2018), pp. 2767-2779 Google Scholar

[45]. L. Chaib, A. Choucha, S. Arif Optimal design and tuning of novel fractional order PID power system stabilizer using a new metaheuristic Bat algorithm Ain Shams Eng. J., vol. 8 (2) (2017), pp. 113-125 Google Scholar.

[46] B.B. Adetokun, C.M. Muriithi Application and control of flexible alternating current transmission system devices for voltage stability enhancement of renewable-integrated power grid: A comprehensive review Heliyon, vol. 7 (3) (2021) Google Scholar

[47] R. Komiyama, Y. Fujii Optimal integration assessment of solar PV in Japan's electric power grid," Renew. Energy, vol. 139 (2019), pp. 1012-1028 View PDF View article View in Scopus Google Scholar

[48]. A. Tbaileh, C. Mishra, K. Thomas PV impacts on dynamic voltage stability in Southeast Con 2017, IEEE (2017), pp. 1-5 View at publisher Cross ref Google Scholar.

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Department of Electrical and Electronics, Faculty of Engineering, Nigerian Defence Academy, Kaduna.

[49]. D.S. Kumar, A. Sharma, D. Srinivasan, T. Reindl Stability implications of bulk power networks with large scale PVs Energy, vol. 187 (2019), Article 115927 View PDF View article View in Scopus Google Scholar.

[50]. R.K. Varma, S.A. Rahman, T. Vanderheide New control of PV solar farm as STATCOM (PV-STATCOM) for increasing grid power transmission limits during night and day IEEE Trans. Power Deliv., vol. 30 (2) (2014), pp. 755-763 Google Scholar.

[51]. M. Gayatri, A.M. Parimi, A.P. Kumar A review of reactive power compensation techniques in microgrids Renew. Sustain. Energy Rev., vol. 81 (2018), pp. 1030-1036 View PDF View article View in Scopus Google Scholar.

[52]. A. Narain, S. Srivastava An Overview of Facts Devices Used for Reactive Power Compensation Techniques power, vol. 2 (2015), p. 3 Google Scholar.

[53]. A.A. Athamneh, W.-J. Lee Benefits of FACTS devices for power exchange among Jordanian interconnection with other countries 2006 IEEE Power Engineering Society General Meeting, IEEE (2006), p. 7 pp. View at publisher Cross ref Google Scholar.

[54]. P.S. Georgilakis, N.D. Hatziargyriou Unified power flow controllers in smart power systems: models, methods, and future research IET Smart Grid, vol. 2 (1) (2019), pp. 2-10 View at publisher Cross ref View in Scopus Google Scholar.

[55]. R. Nivedha, R.N. Banu, A.O. Prakash Enhancement of grid power transmission limits using photovoltaic solar farm as STATCOM (PV-STATCOM) 2016 International Conference on Computing Technologies and Intelligent Data Engineering (ICCTIDE'16), IEEE (2016), pp. 1-6 Google Scholar.

[56]. A. Swandaru, M.D. Rotaru, J.K. Sykulski Intelligence based coordination of large-scale grid-connected photovoltaic systems 2016 51st International Universities Power Engineering Conference (UPEC), IEEE (2016), pp. 1-6 View in Scopus Google Scholar.

[57]. Rad Stanev, Technical University of Sofia; Kamen Nakov, Technical Unversity of Sofia. Power System Stabilizers for Inverter Dominated Future Power Systems June 2020 DOI:10.1109/SIELA49118.2020.9167134 Conference: 2020 21st International Symposium on Electrical Apparatus & Technologies (SIELA).

[58]. Ulbig, Andreas & Borsche, Theodor & Anderss Impact of Low Rotational Inertia on Power System Stability and Operation. IFAC Proceedings Volumes (IFAC-Papers Online). 19.

[59]. Sun, Z. et al. modeling method for the real-time simulation of bridge-based high switching frequency power electronic converters. IEEE Trans. Power Electron. 39, 11723–11731 (2024).

[60]. Intissar Hattabi, University of Blida; Atssa Kheldoum, Unversity of Boumerdes; Rafik Bradai, University of Blida; Soufian Khettab, University of Blida. Enhanced power system stabilizer tuning using marine predator algorithm with comparative analysis and real time validation Springer Nature Scientific Reports November 202414(1) DOI:10.1038/s41598-024-80154-2 License CC BY-NC-ND 4.0

[61]. Blade shape optimization of Savonius wind turbine using radial based function model and marine predator algorithm. https://doi.org/10.1016/j.egyr.2022.09.062.

[62]. Energy efficiency measures in existing buildings by a multiple-objective optimization with a solar panel system using Marine Predators Optimization Algorithm.

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https://doi.org/10.1016/j.solener.2023.112208.

[63]. Sustainable pavement maintenance and rehabilitation planning using the marine predator optimization algorithm. h t t p s: / / d o i. o r g / 1 0. 1 0 8 0 / 1 5 7 3 2 4 7 9. 2 0 2 2. 2 0 9 5 4 0 7.

[64]. Marine predators' algorithm for optimal allocation of active and reactive power resources in distribution networks. h t t p s: / / d o i. o r g / 1 0. 1 0 0 7 / s 0 0 5 2 1 - 0 2 1 - 0 6 0 7 8 - 4

[65]. Review of Wide-Area Controllers for Supporting Power System Stability NICOLAS MIRA-GEBAUER 1 , (Student Member, IEEE), CLAUDIA RAHMANN 2 , (Member, IEEE), RICARDO ÁLVAREZ-MALEBRÁN 3 , (Member, IEEE), AND VIJAY VITTAL 4 , (Life Fellow, IEEE) 1Faculty IV–Electrical Engineering and Computer Sciences, Technische Universität Berlin, 10587 Berlin, Germany 2Department of Electrical Engineering, University of Chile, Santiago 8320000, Chile 3Department of Electrical Engineering, Universidad Técnica Federico Santa María, Santiago 8940000, Chile 4Department of Electrical Computer and Energy Engineering, Arizona State University, Tempe, AZ 85281, USA Corresponding author: Nicolas Mira-Gebauer (nicolas.mira@mail.tu-berlin.de)

[66]. S. Lu, N. Samaan, R. Diao, M. Elizondo, C. Jin, E. Mayhorn, Y. Zhang, and H. Kirkham, ''Centralized and decentralized control for demand response,'' in Proc. ISGT, Jan. 2011, pp. 1–8.

[67]. M. Shahraeini, M. H. Javidi, and M. S. Ghazizadeh, ''Comparison between communication infrastructures of centralized and decentralized wide area measurement systems,'' IEEE Trans. Smart Grid, vol. 2, no. 1, pp. 206–211, Mar. 2011.

[68]. M. Jing, in Power System Wide Area Stability Analysis and Control, 1st ed. Hoboken, NJ, USA: Wiley, 2018.

[69]. D. K. Molzahn, F. Dorfler, H. Sandberg, S. H. Low, S. Chakrabarti, R. Baldick, and J. Lavaei, ''A survey of distributed optimization and control algorithms for electric power systems,'' IEEE Trans. Smart Grid, vol. 8, no. 6, pp. 2941–2962, Nov. 2017.

[70]. X. Liu, X. Zeng, L. Yao, G. I. Rashed, and C. Deng, ''Power system state estimation based on fusion of WAMS/SCADA measurements: A survey,'' in Proc. 2nd IEEE Conf. Energy Internet Energy Syst. Integr. (EI), Beijing, Oct. 2018, pp. 1–6.

[71]. A. Mao, C. Xiong, S. Luo, S. Zhao, and D. Zhang, ''An approach of state estimation based on process measurement data,'' in Proc. Asia–Pacific Power Energy Eng. Conf., Wuhan, Mar. 2009, pp. 1–6.

[72]. B. Quartey, D. Shaw, and P. Waked, ''An application of PLCs as an RTU in SCADA systems,' in Proc. Rec. Conf. Papers Ind. Appl. Soc. 39th Annu. Petroleum Chem. Ind. Conf., 1992, pp. 271–274, doi: 10.1109/PCICON.1992.229301.

[73]. P. M. Joshi and H. K. Verma, Synchrophasor measurement applications and optimal PMU placement: A rreview, Electric Power Syst. Res., vol. 199, Oct. 2021, Art. no. 107428.

[74]. M. Sarkar and B. Subudhi, ''Fixed low-order synchronized and nonsynchronized wide-area damping controllers for inter-area oscillation in power ssystem, Int. J. Electr. Power Energy Syst., vol. 113, pp. 582–596, Dec. 2019.

[75]. R. Gore and M. Kande, ''Analysis of wide area monitoring system architectures,'' in Proc. IEEE Int. Conf. Ind. Technol. (ICIT), Seville, Spain, Mar. 2015, pp. 1269–1274.

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JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 13(4), DECEMBER, 2025
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

[76]. H. Bevrani, M. Watanabe, and Y. Mitani, An introduction on power sysmonitoring,ng," in Wide Area Power System Monitoring and Control, 1st ed. Hoboken, NJ, USA: Wiley, 2014.

[77]. A. Sharma, B. Sahu, N. P. Triphathy, L. K. Nagar, and N. P. Patidar, "Time latency compensation for wide area damping controller," in Proc. 6th IEEE Power India Int. Conf. (PIICON), Delhi, Dec. 2014, pp. 1–6.

[78]. B. Naduvathuparambil, M. C. Valenti, and A. Feliachi, "Communication delays in wide area measurement ssystems, in Proc. 34th Southeastern Symp. Syst. Theory, 2002, pp. 118–122.

[79]. X. Yang and O. Marjanovic, "LQG control with extended Kalman filter for power systems with unknown time-delays," in Proc. 18th World Congr., 2011, pp. 3708–3713.

[80]. B. P. Padhy, S. C. Srivastava, and N. K. Verma, "A wide-area damping controller considering network input and output delays and packet drop," in IEEE Trans. Power Syst., vol. 32, no. 1, pp. 166–176, Jan. 2017.

[81]. M. Liu, I. Dassios, G. Tzounas, and F. Milano, "Stability analysis of power systems with inclusion of realistic-modeling WAMS delays," IEEE Trans. Power Syst., vol. 34, no. 1, pp. 627–636, Jan. 2019.

[82]. A. Papachristodoulou, M. M. Peet, and S.-I. Niculescu, Stability analysis of linear systems with time-varying delays: Delay uncertainty and quenching," in Proc. 46th IEEE Conf. Decis. Control, New Orleans, LA, USA, Jun. 2007, pp. 2117–2122, doi: 10.1109/CDC.2007.4434764.

[83]. W. Michiels, V. V. Assche, and S. I. Niculescu, "Stabilization of time-delay systems with a Controlled time-varying delay and applications," IEEE Trans. Autom. Control, vol. 50, no. 4, pp. 493–504, Apr. 2005.

[84]. The Arctic University of Norway: Department of Electrical Engineering; Impact of Inverter Based Resources on System Stability in Low Inertia Power System; Network Hasnain Zafar Raja. Candidate No: 9. Master's thesis in Electrical Engineering, ELE-3900, May 2023.

[85]. Volume 12 December 2024, Pages 4983-4997 Energy Reports Research Paper Impact of variable renewable energy sources on the power system frequency stability and system inertia Authors: Godfrey Macharia Njoka, Lucas Mogaka, Agnes Wangai.

[86]. F. Shen, *et al.* Inertia estimation of power system with new energy considering with high renewable penetrations Energy Rep., 9 (Sep. 2023), pp. 1066 1076, 10.1016/j.egyr.2023.04.147 Google Scholar.

[87]. A. Maulidhia, D. Asfani, A. Priyadi, and H. Setiadi, Frequency Stability Analysis On Optimization Of Virtual Inertia Control (VIC) Capacitor Energy Storage (CES) Controller Settings Using Particle Swarm Optimization, in *2022 International Conference*.

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