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Review article

Power system stability with high integration of RESs and EVs: Benefits, challenges, tools, and solutions

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ABSTRACT

In our daily lives, electric energy is essential and impacts numerous aspects of society. The electricity produced from conventional sources falls short of meeting contemporary demand, giving rise to power supply issues and environmental concerns, including the emission of greenhouse gases. For all those reasons, the transformation to Renewable Energy Sources (RESs) is indispensable, more than ever. Nevertheless, the inherent uncertainty and low inertia introduce operational challenges and threaten power system stability. Various research papers have been published regarding RES integration and design. However, research articles addressing stability in distributed generation networks with RESs are either scarce or inadequate. To address power system stability, the primary objective of this paper is to provide a comprehensive review of the benefits, challenges, and integration of RESs and electric vehicles (EVs), in addition to tools, software, controlling mechanisms, and potential solutions related to RESs integration. Integrating HVDC technology with hybrid RES enhances long-distance power transmission efficiency, reduces losses, and improves grid stability, making it an effective solution for variable RES generation. Therefore, the HVDC link has been taken as a case study and is simulated using DIgSILENT /MATLAB softwares. The result shows that the HVDC link is more stable than the HVAC transmission in terms of voltage stability when integrating the RESs, which could result in a voltage limit violation. The 100 % RESs integration may proceed more smoothly and efficiently if DC voltage is present.

1. Introduction

Electric energy is crucial for our daily routine activities, including heating and cooling, lighting, transportation, electric vehicles, communication, manufacturing and industry, healthcare, education, entertainment, food preservation and preparation, infrastructure and public services, research and innovation, and economic growth. Briefly, energy is the currency of the universe. Unfortunately, more than 90 % of this energy is still generated from fossil fuels as shown in the pie chart in Fig. 1.

The electricity generated from traditional sources struggles to fulfil current demands, leading to power supply challenges and exacerbating environmental issues, such as greenhouse gas (GHG) emissions. Global warming has become a critical global issue. International agreements have been initiated to conquer these challenges by expanding renewable energy sources (RESs) utilisation while diminishing GHG emissions (Mubaarak et al., 2020). For all those reasons, the transformation to RESs has become more indispensable than ever. Benefits from such a transition include enhanced overall system diversity and dependability, decreased transmission losses, and localized power generation (Saxena et al., 2024). Even though some RESs have limitations like geographic constraints and inherent variability, their growth has been substantial in recent years, as shown in Fig. 2 which also compares the shares of RES and non-renewable energy sources between 2001 and 2021. It is

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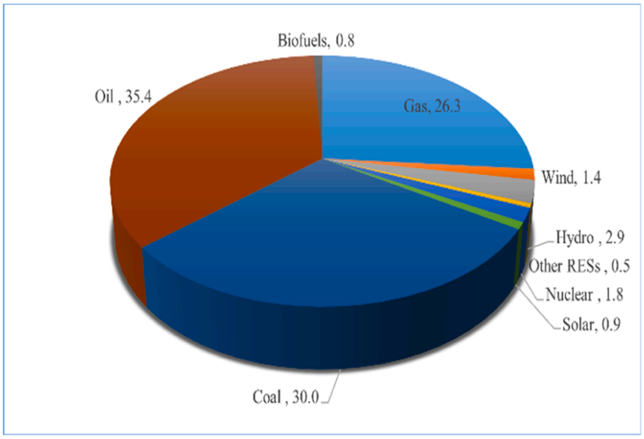

Fig. 1. Global Primary Energy Consumption by Source 2022 (Mubaarak et al., 2020).

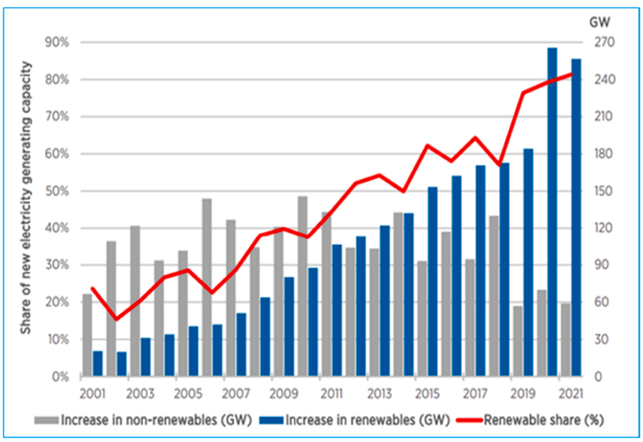

Fig. 2. Annual Power Capacity Growth of Renewable Energy (Anderson and Fouad, 2008).

noticeable that RESs have shown substantial growth throughout the depicted period, while the usage of non-renewable sources fell starting in 2011 and going onward. The highest increase in the share of RESs was witnessed in 2020 at 260 GW. In contrast, the growth in non-renewable usage was about 70 GW in the same year. Hybrid Renewable Energy Sources (HRES) combine two or more energy sources to produce electricity.

Applying HRES is a contemporary trend in the energy sector. Several countries are planning to utilize energy hybridization. Various proposals have been offered to maximize the utilization of diverse RESs to produce energy more sustainably and effectively (Khosravani et al., 2023). Over the past few decades, solar photovoltaic (PV) and wind farms (WFs) integration has garnered significant attention from utilities and research centres globally aimed at cost reduction. This integration has been successfully adopted among all available RESs (Elkadeem et al., 2019). Another goal of HRES is to meet the increased energy demand (Pandiyan et al., 2022). Despite RESs' potential to

produce power more consistently, their unpredictability affects the overall balance between generation and the associated load which already has inherent variability and uncertainty (Saleh et al., 2024). Consequently, the variation in active and reactive power generation significantly affects bus voltage and frequency systems.

1.1. Overview of power system stability

In general terms, power system stability is defined as the ability of a power system to stabilize itself after being displaced by physical events like faults, lightning strikes, sudden changes in load generation (Machowski and Bialek, 2008a). Similar to a thermometer, it provides one of the core indicators for the general health and performance of the network. The rationale behind this measure is threefold: Stability of a power network equals reliability of power; outages can obviously lead to economic losses, and it is imperative to assess the financial impact of outages. Thus, a robust network can increase the economic results of enterprises, increase the productivity of industries, and raise the quality of life of the population. Power systems stabilityprevents power failure which causes large economic damages. Providing uninterrupted power helps businesses to run more effectively, minimizing downtime and cost, and aiding economic growth and stability. A stable power system will maintain an acceptable range of voltage and frequency so that electrical devices are protected. Stable voltage is essential for prolonged and safe functioning of electrical devices. Cascading failures from an unstable or failed electrical system component can directly cause widespread electrical outages and potentially collapse the entire system. A stable power system can prevent these cascading events, thereby maintaining the integrity and continuous operation of the electrical grid. In summary, power system stability is essential for ensuring the reliability, economic efficiency, safety, and resilience of the electrical network (Saleh et al., 2024).

1.2. Motivation and contribution

Fig. 3 demonstrates how diverse the literature on RES integration and design is there, showing the number of research papers published on RES in 2019–2023 (PubMed data). However, Fig. 4 reveals a scarcity or inadequacy of research papers focusing

on enhancing stability in distributed generation networks utilizing HRES during the same period and data source (PubMed). Furthermore, as shown in Table 1 the previous review was carried out from a specific perspective. In contrast, the purpose of this review is to cover all relevant issues of power system stability, particularly from the perspective of the significant penetration of RESs, and the Methodology Employed for Conducting the Review is shown in Fig. 6. Although it is often easier to discuss the power system in terms of a "steady state," in actuality, such a state never occurs. There are always going to be unexpected variations in power generation of PV and wind turbines and other generterrs, network faults, equipment malfunctions, unexpected application of a significant load, and loss of a line or largest generating unit. So, we must quickly ensure the stability of the electricity system in all these situations (Anderson and Fouad, 2008). Thus, the primary motivation for writing this paper is to provide an extensive review of publications on power system stability. The layout and the major contribution of this review paper can be summarised as follows: Section 2 introduces a brief of the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of the widespread renewable energy sources to give insight into the characteristics of RES and how it is related to power system stability. The importance of energy hybridization as an approach to increase power systems' diversity and reliability and lessen their weaknesses and dependence on a single variable energy source is explained in this section. Section 3 shows how this hybridization of energy sources introduces economic and environmental benefits due to local energy generation and loss network reduction. Although this hybridization brings advantages, it also presents new challenges. This Section also briefly discusses these challenges in the field of HRES. The biggest challenges faced at HRES include keeping the power system running smoothly, ensuring system stability whatever the changes in RES generation or demand, or occurring external disturbances like faults. The power system stability with integrated RES is discussed in Section 4, along with the elements that might put stability at risk, such as a decrease in system inertia, short-circuit level and Reactive Power injection/absorption brought on by RESs connected through power electronic converters. The transportation system should be part of the

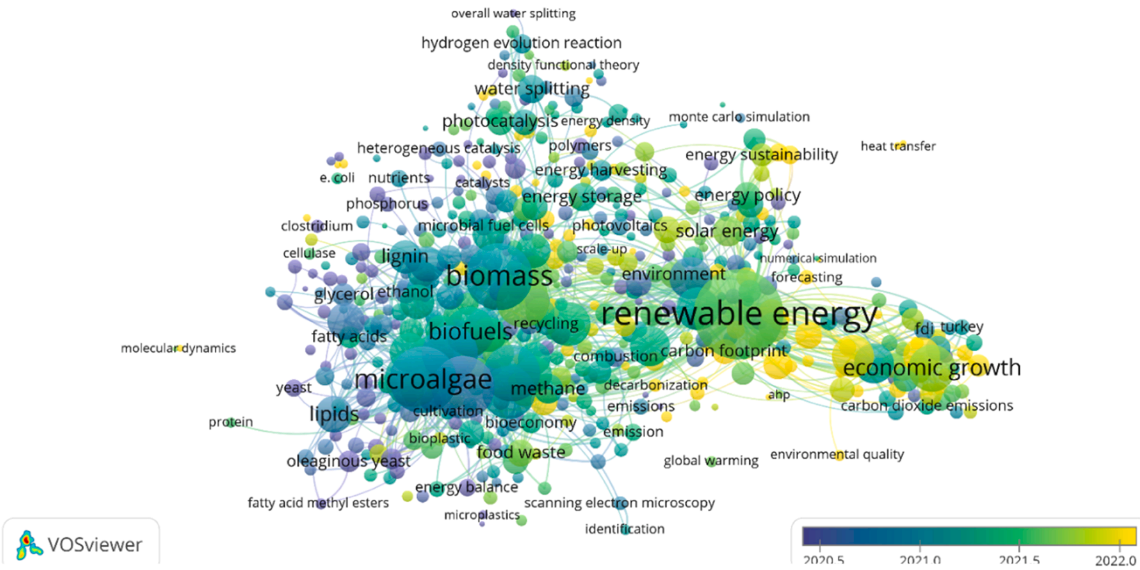

Fig. 3. Renewable energy sources publications, 2019–2023 (PubMed data).

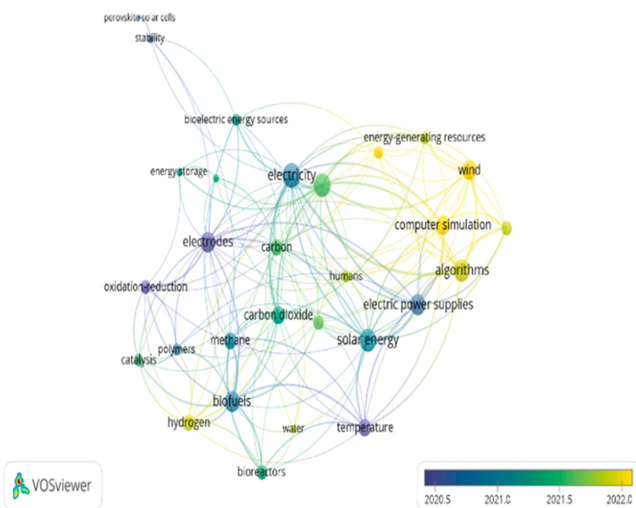

Fig. 4. RES publications considering Power system stability.

energy transition to minimise GHG emissions, electric vehicles (EV) are another term that will affect the system's stability. Section 5 introduces the possibilities of the EV integration paradigms and gives an idea about the service provided with each paradigm to enhance the system's stability. With all these components (i.e. RESs and EVs) the power system becomes more complex due to stochastic and big data; therefore, advanced analysis methods are necessary. Section 6 highlights the methods, tools and software utilized to power system analysis. The computation result is required to analyze, forecast, optimize, evaluate, and control the risk associated with the regulation, design, testing, and validation of power system operation. Certain situations include real-time monitoring, which uses these results to adjust system settings to achieve the system's stability. Section 7 explores various solutions and cutting-edge technologies for enhancing power system stability along with HRSs. Section 8 addresses controlling mechanisms for RES integration while considering power system stability. Finally, Section 9 takes the case study of showing how the integration of RESs may cause overvoltage of some buses. For the same system, the two parts are connected through the power electronic devices (i.e., the rectifier and inverter) using a high voltage direct current (HVDC) transmission line. This interconnection facilitates the smooth integration of RESs due to its inherent feature of supporting Direct Current (DC) voltage. In summary, the need for high integration of RESs and EVs has become inevitable to mitigate energy demand and address environmental challenges. However, the inherent uncertainty of these integrations poses challenges and concerns regarding power system stability. This research aims to answer the following questions: Why is power system stability a concern with the high integration of RESs and EVs? What technologies and solutions can address these challenges? What are the tools of power system analysis in managing these complex systems? The overall aim is to help the power system operator find smooth operations and minimize the difficulties with that integration. Additionally, it aids academic

Table 1
Comparison of Main Contributions: This Review vs. Most Similar Previous Review Papers related to Power System Stability (PSS).

Ref.	SWOT Analysis of RES	Benefits and Challenges of HREs	PSS with High Integration of RESs	Electric Vehicles and PSS	Tools for PSS Analysis	Solutions and Technologies	Controlling Mechanisms	Case study and simulation
(Pandiyan et al., 2022)	√	×	×	×	√ (design tools)	√	×	×
(Hassan et al., 2023a)	√	√	√	√	×	Only storage units	control strategies of on/ Off-grid system	×
(Tan et al., 2021)	×	√ challenges of ESS integration	ESS supporting	√	×	Only storage units	×	×
(Sinsel et al., 2020)	×	√	√	×	√	√	×	×
Our review	√	√	√	√	√	√	√	√

researchers in gaining a forward-looking perspective on the future of power systems, the layout of the paper is shown in Fig. 5.

2. Brief SWOT analysis of renewable energy sources

Balancing power generation with demand while maintaining system resilience against supply disruptions requires a multifaceted approach combining technological, operational, and policy-based strategies. In terms of HRESs, it is crucial to understand and evaluate the Strengths, Weaknesses, Opportunities, and Threats (SWOT) associated with RESs power plants' characteristics and establishment. SWOT analysis improves system planning, helps in decision-making, and decreases risk by determining the internal and external factors that can threaten the system's stability.

Table 2 shows the brief SWOT analysis of the most widespread RESs and Hydrogen, showing that the most stable RESs are hydropower plants that can be dispatchable generation, therefore, the power network with high integration of these hydropower plants seems more stable than the network of solar power plants. The table shows that the integration of individual energy sources may threaten the stability of the system due to the inherent intermittency, thereby the integration of different sources into the system all together will mitigate the stability. For instance, the combination of wind turbines with hydroelectric power plants will be more stable than the integration of just one source. In the case of wind integration only, wind speed may be lower/upper than the acceptable limit of the turbine characteristics causing the turn-off of the turbine. Furthermore, if some places are windy, and others are not, integrating various energy sources into large regions will aid in energy harvesting in those locations and consistent energy sharing will be made possible through this large integration and collaboration of major utilities to avoid the threats and weaknesses of individual RESs. Sharing energy resources across regions through interconnected grids increases overall system flexibility and reliability. For example, importing renewable energy from regions with abundant resources can offset deficits in limited-resource areas. Establishing regional energy markets enables the efficient allocation of resources and facilitates the integration of surplus renewable energy from neighboring regions. Providing subsidies and tax benefits for hybrid systems encourages the deployment of diverse energy sources. Supporting research into advanced storage solutions and hybrid systems enhances the cost-effectiveness and scalability of renewable integration. Establishing policies that mandate resilient system designs, such as backup power solutions or minimum storage capacities, ensures system stability during supply disruptions. In regions like Northern Europe, limited solar energy during winter months is compensated by wind power and hydro resources, combined with significant battery storage and robust demand-side management strategies. Similarly, hybrid systems in rural parts of Africa integrate solar, wind, and biomass to ensure energy availability and resilience. It is worth concluding that as Hydrogen is versatile in usage, it can be used as an energy storage system with high energy density, which will mitigate the system's stability because of the integration of variable RESs Figs. 6 and 7.

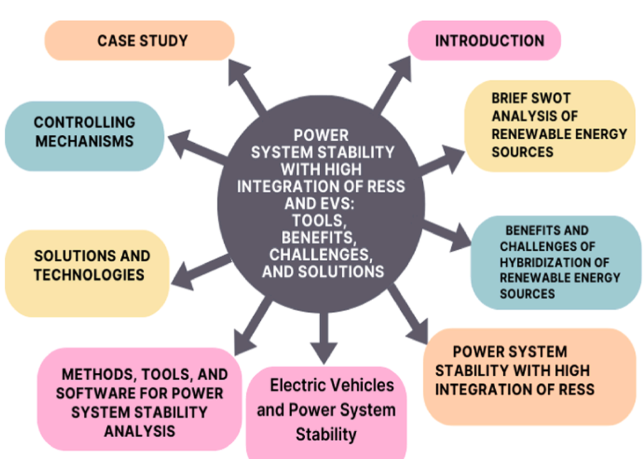

Fig. 5. Paper layout.

3. Benefits and challenges of hybridization of renewable energy sources

3.1. Benefits of hybridization of RESs

Energy is indispensable in our everyday routines, such as food and water. Electrical energy has considerable benefits, qualifying for convenient and efficient transformation into various forms of energy such as heat, light, and motion. Moreover, it is a cost-effective, easily controllable, and efficiently transmittable energy source over long distances. The downside is that a significant portion of this energy is currently obtained from unsustainable resources like fossil fuels, which are finite and gradually running out. Consequently, many governments are implementing policies aimed at transitioning to RES. Notably, Asia now contributes 42 % of global renewable energy generation, followed by Europe (19 %), North America (18 %), South America (11 %), and Eurasia (5 %) (International Renewable Energy Agency, 2020). The primary advantages of energy transition lie within their economic and environmental impacts. While sustainable energy projects often require a substantial initial capital investment, they typically do not experience ongoing operation fuel expenses. Using less fuel not only reduces carbon emissions but also helps achieve sustainable development goals by using RESs to close the gap in the energy sector. This transition will also enhance healthcare services by preventing energy disruptions that adversely affect hospitals, causing patient fatalities, expired medications, and related issues particularly evident in conflict-ridden regions. Moreover, improvements in the education system will enable prolonged use of the internet and computers by students, bypassing the limitations of backup power/Uninterruptible Power Supply (UPS). Industries, commerce, and agricultural systems will function efficiently, resulting in cost savings.

However, the uncertainty of RESs such as the darkness or variations in wind speed which in some cases lead to the shutdown of the generator at high/ low speed.

HRES improves the overall stability and dependability of energy generation by reducing the intermittency problems associated with individual RESs. While wind power can be used even when there is less sun exposure, solar power reaches its maximum production during the day (Hassan et al., 2023c). By combining various sources, the energy supply is more reliable and there is less chance of blackouts during severe weather (Hassan et al., 2023a).

Therefore, HRES introduces energy source diversity for the functioning of the electrical grid, and end users through hybrid local power generation and energy storage. This paradigm of local generating power led to decreasing the power loss and enhancing the system efficiency. Moreover, HRES has an impact on improving the quality of regional electric power, particularly in distributed systems. To enable frequency control, peak demand reduction, and peak power supply flexibility in the grid (Aktaş, 2021), it also makes use of energy storage solutions. The forthcoming sections will detail how these benefits are integrated into the system. Furthermore, HREs not only reduce the operating cost of energy generation but it is one solution to mitigate climate change problems by using clean RES and avoiding GHG emissions. The overall benefits of HRES can be summarised as the economic and environmental benefits.

3.2. Challenges of establishing HRESs

The establishment of an HRES offers many advantages, but it also brings obstacles. This section provides a concise overview of these

Table 2
Brief SWOT analysis of RESs and hydrogen.

Type	Strengths	Weaknesses	Opportunities	Threats	Ref.
Solar PV Power Plant	Unlimited Solar Potential	Intermittency at night	Establish new business prospects	Solar panel disposal and health risks	(Guangul and Chala, 2019a) (Moharram et al., 2013)
	Eco-friendly	Lower efficiency < 25 %	Growing Concern using	Policy discontinuity consequences	Maka and Alabid (2022) Jathar et al., (2023)
	Easily harvesting and utilizing	Space requirement	Conventional Sources	Energy mix	Wang et al., (2021)
	Lower net cost	High installation cost	Solar Tech. advancements and cost reduction	Fossil fuel dominated	
	Diverse applications	Shading impact	Government incentive growth		
	Low maintenance				
Wind power plant	Fossil Fuel Mitigation	Fluctuation and Intermittency	Governmental Renewable Focus	Policy Uncertainty	(Baidya and Nandi, 2020) (Hassan et al., 2023b) (Guangul and Chala, 2019b)
	Green and Renewable	High investment costs	Wind Tech. Advancements and Cost Reduction	Wildlife Impact	
	lower operating costs	Geographical Restriction		Residents' opposition	Hassan et al., (2023a) (Santelo et al., 2022)
	Less Space Requirement	Maintenance and grid Constraints	Offshore Wind Development	May fall on the worker	
	Scalability	Noise and Aesthetics		Failures and shutdown	
	High energy yield		improve the local economy		
Hydro-power plant	Stable energy generation	High investment costs	Small Hydro plant availability	Unclear regulations	Igliński, (2019)
	Green and renewable	Completing a project takes time.	Development Paths	Low Investor Interest	Tan et al., (2021) (Sibtain et al., 2021) (Kumar et al., 2022)
	Established Hydro Tech.	Fish Population and Environmental Impact	Reservoirs as ESs and Tourism Potential	Technological Obstacles and Obsolescence and Infrastructure	Blakers et al., (2021)
	Reliable and Predictable	Seasonal variations	Cost Savings and Social Benefits	May affect on climate change	
	Scalability	Long-Term Drought Limitation	Flood Risk Management	Financial Difficulties of Costly Equipment	
	Hydro storage and grid enhancement	Limited Hydro Site availability			
H_2	Clean Energy	Transporting,	Eco-friendly	regulations pose risks	
	High energy density storage	High production,	RESs integration	inadequate supply chain	Khan and Al-Ghamdi, (2023) Zhang et al., (2024)
	Versatility in usage	Storage costs	less environment impacts	less competition with other RESs	

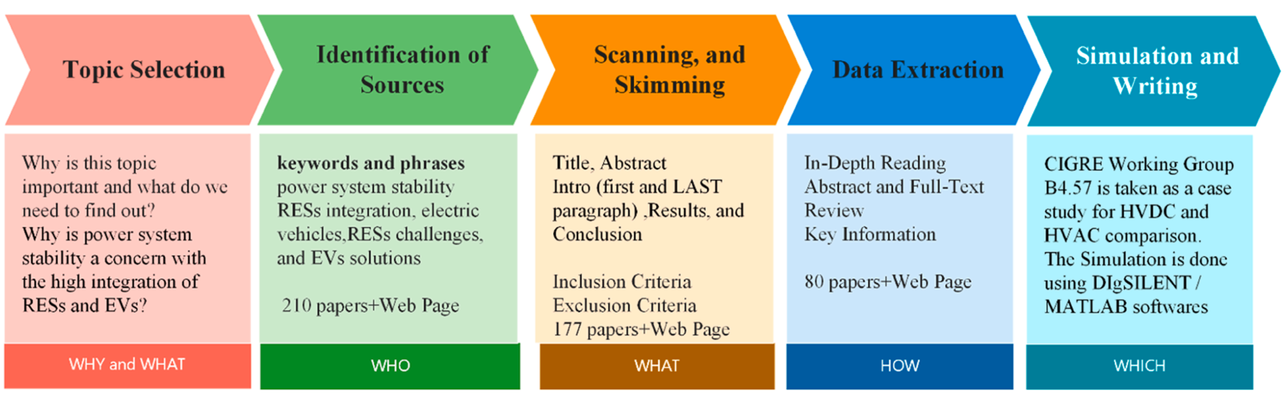

Fig. 6. Methodology employed for conducting the review.

challenges. Addressing these issues is essential for fostering the further expansion of sustainable energy utilization (Saleh and Mahmood, 2022).

According to research (Kabeyi and Olanrewaju, 2022), in contrast to sustainable development, which is based on social, economic, and environmental pillars, a five-dimensional approach that considers environmental, economic, social, technical, institutional/political, and technical sustainability is the most effective way to analyse energy integration. These challenges can be summarized in Table 3.

However, this research focuses on the technical obstacles that encompass fluctuations in power output linked to weather conditions, the contribution of reactive power, thus voltage stability at the Point of Common Coupling (PCC), and fault ride-through capabilities. The proceeding section introduces specifically the power system stability with high integration of RESs.

3.3. Policy frameworks and regulatory mechanisms for successful RES integration

Inertia and flexibility being crucial elements to realize the seamless integration of RESs into existing power grids, a broad range of policy frameworks and regulatory mechanisms is needed that will focus not only to improve RESs' penetration but also to stabilize the grid, absorb variability, and increase the overall resilience of the system. In particular, the enactment of long-term renewable energy goals, for instance, at the national Renewable Portfolio Standards (RPS) or Renewable Energy Incentive programs that send market signals and provide long-term certainty for investors. Such targets gave rise to financial incentives such as feed-in tariffs or tax can reduce upfront capital costs of RES projects and allow them to be more competitive than conventional power production. These incentives can drive down the levelized cost of

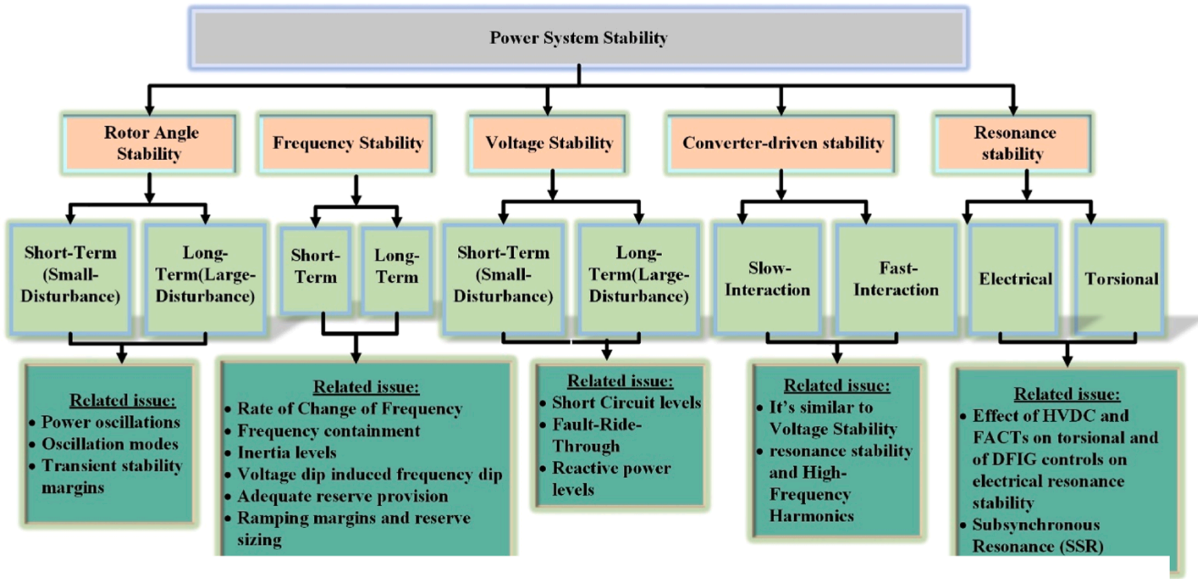

Fig. 7. Power system stability classification.

Table 3
Summarized challenges of establishing HRESs.

Challenges	Description	Ref.
Economic	High initial costs. Limited bank loan access to investment in sustainable projects Insufficient funding. Revenue Impact on Loan Repayment (Payment Risk)	(Taghizadeh-Hesary and Yoshino, 2020) (Tsao et al., 2021)
Technical	Stability issues due to the unpredictable nature of RESs, and inertia reduction. Limited in size, restricted by location, and mostly non-synchronous kinds. Settings of protection system issues due to bidirectional power flow. Planning is a difficult process. Inadequate maintenance of the equipment and management. Technical and commercial uncertainty. Insufficient solar/wind data at locations.	(Sinsel et al., 2020) (Sánchez-Jacob et al., 2021) Machowski and Bialek (2008b) (Rehman et al., 2022)
Policy Related	Deficiency of regulations to promote growth. Governments ought to implement tax incentives to encourage investments in RES technology	(Akpahou et al., 2024), Yan et al., (2023)
Institutional	Few research and development (R& D) facilities exist worldwide Absence of an institutional structure. Absence of clear transparency concerning the extent of the difficulties and the technologies accessible to resolve these challenges related to RES integration. Limited laboratory and innovation centres.	(Sirin and Yilmaz, 2021) (Shahsavari and Akbari, 2018)
Social	Insufficient knowledge and consciousness. Insufficient skilled labour available locally to construct, design, run, and maintain a RESs plant.	Briggs et al., (2022) Yaqoot et al., (2016)

energy and speed up the adoption of RESs and promote renewable power as a viable solution (Yesilbudak and Colak, 2018)

Besides the renewable energy targets, designing the market mechanisms that can adopt the intrinsic intermittency and variability of RESs. Short demand response for the electricity markets should be flexible enough to include mechanisms such as real-time pricing, capacity markets, and ancillary service markets for frequency regulation or voltage support. These services enable grid operators to maintain system balance with high levels of variable generation. This would and ensure that grid operators are able to keep generation and demand in balance even if RES generation output is less controllable. Additionally, in order to reveal the integration policies, the access to the grids should be facilitated; the decentralized RESs, which are integrated, should have open access to the grids, as such as rooftop solar and small-scale wind farms, to join the grid easily without encountering undue barriers or restrictions.

One of the key solutions for a successful RES integration is the usage of energy storage technologies. Policies should decide on the efforts on the areas of developing and operating energy storage systems (ESSs), and on battery energy storage systems (BESS), pumped hydro storage (PHES) and hydrogen energy storage (HES), which can take in excess renewable energy when generation is higher than demand and inject it during periods of low generation. These systems help smooth out which helps mitigate fluctuations in renewable energy generation, offering balance to thegrid. Governments should incentivize energy subsidies or tax credits to lower the initial cost burden of storage deployment. Additionally, demand response (DR) programs should be offered with incentives so that consumers can alter their energy consumption depending on grid conditions. Dynamic pricing models such as time-of-use (ToU) pricing or real-time pricing can also help facilitate consumer shifts in energy use to times of renewable energy abundance, helping to balance supply and demand as well as alleviate pressure on the grid at peak times (Khan et al., 2022).

Flexible grid infrastructures also play an important role in this. Smart grids enabling real-time communication and control among energy consumers, producers, and storage systems is crucial for addressing the complexities due to high RES penetration. Governments should enable use of DR systems, and advanced grid control technologies enabling grid operators to manage the flow of power, improving availability and resiliency in a dynamic manner. Flexible AC transmission systems (FACTS) and high-voltage direct current (HVDC) transmission could also play its part by enabling the long-distance transmission of renewable energy, which also lowers grid congestion and increase grid stability (Shah et al., 2024).

Moreover, Secondly, policy frameworks should also support interconnection between grids enabling countries or regions to share surplus renewable energy." This is particularly critical in resource-constrained areas, because they can import clean energy from nearby geographical areas abundant in renewable resources. The cross-border energy trading platforms enable outspread energy allocation across regions, increasing grid system stability & flexibility. In an effort to support the deployment of new technologies such as grid-scale energy storage, next-generation inverters and digital grid technologies, public-private partnerships (PPPs) can also play an essential role in catalyzing innovation, financing and the deployment of new technologies. Lastly, R&D support is needed to encourage innovation in grid technologies and energy storage knowhow. Governments should invest in R&D initiatives aimed at improving the efficiency, scalability, and cost-effectiveness of renewable energy technologies. In addition, they can also fund pilot projects and demonstration initiatives to facilitate the commercialization of emergent technologies and contradict the financial risks taken for early-stage projects. Germany's Energiewende, for example, demonstrates how a coordinated policy framework can enable the integration of high RES penetration into the grid. Through a combination of financial incentives, long-term renewable energy targets and flexible grid infrastructure, Germany has built a high-resilience grid that allows it not only to significantly increase its reliance on RESs while ensuring the system's stability. The Energiewende also highlights the need to connect grids across Europe, allowing Germany to import and export renewable energy, making a more stable and reliable power generation system (Chen, 2024).

4. Power system stability with high integration of RESs

The stability of a power system is primarily influenced by its initial operating conditions and the type of disturbances it encounters. When a disturbance occurs in a power system, it can impact various components within the system. This, in turn, leads to observable alterations in parameters such as system frequencies, voltage levels, power distribution, and the rotational angles of generators (Kundur et al., 2004). According to these parameters, the power system stability may be classified as given in Hatziargyriou et al. (2020); Luo et al. (2021); Shair et al. (2021). Power system stability guarantees a steady flow of uninterrupted power from its generation to meet demands. It monitors various system components' dynamic responses to disturbances. If stability is not preserved, subsequent events can span from isolated disconnections of some power plants to widespread failures and complete system blackouts. The intrinsic inertia of conventional synchronous machinery plays a crucial role by counteracting initial power

imbalances occurring within the first two seconds after a disturbance event. This action limits the rate of change of frequency (RoCoF) (Drhorhi and Fadili, 2022). However, there is a trend toward establishing a lot of HVDC links and replacing these conventional synchronous machines with power electronic devices connected to renewable energy sources and the rest of the system leading to decreasing the system inertia and making operation and control more challenging (Zografos et al., 2018).

4.1. Decreasing level of inertia

To clarify the interrelation between the inertia constant (Hs in [MJ/MVA ≈ s]) and an imbalance in the electricity produced and consumed ΔPT for the power network comprises N generators, with each generator distinguished by its kinetic energy E_{kinet} when operating a synchronous speed ω_{sm} in [rad/s], and its power capacity is denoted as Si, where 'i' represents an integer identifier. The inertia constant is

$$\mathbf{H_i} = \frac{\mathbf{E_{kinet}}}{\mathbf{S_i}} = \frac{\mathbf{J_i\omega_{sm}^2}}{\mathbf{2S_i}} \tag{1}$$

where Ji is the inertia moment of the synchronous generator rotor (i) in $kg \cdot m^2$.

In the case of a multi-machine system, the equivalent inertia system can be represented as

$$H_s = \frac{HS_{th} + HS_g + HS_{hyd} + HS_{wf} + \quad HS_{pv/csp}}{S_s} \tag{2}$$

where, H_{th} refers to the thermal power plants' equivalent inertia constant≈ 5.5 seconds. H_g refers to the equivalent inertia constant for gas turbine power plants (including combined-cycle power plants) ≈ 5.5 seconds; H_{hyd} refers to the equivalent inertia constant for a turbine Generator≈ 3 seconds (Grainger and Stevenson, 1994); H_{wf} refers to the equivalent inertia constant for wind farms is considered negligible ≈ 0. H_{csp} refers to the equivalent inertia constant for concentrated solar power plants (CSP)≈ 5.5 seconds. H_{pv} refers to the equivalent inertia constant for PV plants is considered negligible ≈ 0. S_{th} refers to the rated power of thermal power plants. S_g refers to the rated power of gas turbine power plants (including combined-cycle power plants); S_{hyd} refers to the rated power of hydro turbine generators; S_{wf} refers to the rated power of wind farms. S_{csp} refers to the rated power of CSP plants, and S_{pv} refers to the rated power of photovoltaic plants. Furthermore, the difference in power between power generation and load (imbalance ΔPT), and RoCoF in terms of inertia constant can be expressed as follows (Drhorhi and Fadili, 2022):

$$\Delta P_T = \frac{2f_i}{f_s^2} \frac{df}{dt} \sum_{i=1}^{N} H_i S_i = P_{meh} - P_{elect} \tag{3}$$

$$\frac{df}{dt} = \frac{\Delta P_T \quad f_s}{2\sqrt{H_s S_s (\Delta P_T t + H_s S_s}} \tag{4}$$

Where, fi = ω/ 2π generator's frequency (i) in [Hz]; ω generator mechanical speed [rad/s]. fs = ωs/2π Electrical grid frequency [Hz]. $\boldsymbol{P_{meh}}$ mechanical power supplied by the prime mover (turbine) [W]. $\boldsymbol{P_{elect}}$ Electrical power output of generator [W].

From the above equations, with greater system inertia, it becomes simpler to manage the frequency deviation rate of change of frequency. This is because the system's inertia effectively resists variation in frequency. The growing incorporation of RESs and the engagement of demand-side participation in system operations have introduced heightened intermittency into the power system. This variability amplifies the challenge of upholding system stability, primarily due to the decline in inertia (Prabhakar et al., 2022) by using power electronic (PE) converters with this integration of RESs (Al-Shetwi et al., 2020). As per the European transmission system operators (TSOs), the foremost power system stability challenges are due to inertia reduction, which ranked with a score of 17.35 (Prabhakar et al., 2022). When compared to a typical plant of the same rating, a wind plant's kinetic energy storage is reduced by a factor of around 1.5 due to its smaller inertia and speed during construction (Machowski and Bialek, 2008a). This redaction will affect frequency stability as well. This integration needs additional attention and rethinking how this effect will be mitigated (Prabhakar et al., 2022). The low inertia issue can be lessened by using the energy storage systems of electric vehicles, which inject or absorb power in reaction to frequency changes, as they become more generally available and come in a wider range of designs and capacities. However, the coordination of operation (charging and discharging of EVs), Electric Vehicle Aggregator, and Demand Response Programs are key roles for effective mitigation. Studies demonstrate that V2G operations significantly enhance grid frequency stability. For instance, simulation results indicate a reduction in the Rate of Change of Frequency (RoCoF) by up to 30 % in systems with high EV penetration. Real-world implementations, such as in Denmark, highlight the successful deployment of EVs in frequency regulation services, showcasing their potential to reduce system vulnerability. This will be taken in detail in Section 5.

4.2. Fault ride through

During the integration of RESs (low-scale power plants), the disconnection of these plants during the fault introduces a low effect on the power system. However, at a large-scale integration will strongly affect the stability of the power system (Al-Shetwi et al., 2020). To demonstrate the relationship between the active power and power angle (δ), let us consider the fundamental circuit for a two-port equivalent circuit, where the shunt branch is ignored, and the series branch has simply an inductance as shown Fig. 8.a. and the phasor diagram equivalent to the circuit is drawn in the figure. OAD and BAC are similar triangles. Triangles BAC and OBC analysis results

in

$$|\mathbf{BC}| = \mathbf{XIcos}\varphi = \mathbf{Esin}\delta\mathbf{thus}, \mathbf{Icos}\varphi = \frac{\boldsymbol{E}}{\boldsymbol{X}}\mathbf{sin}\delta \tag{5}$$

Also,

$|\mathbf{AC}= =\mathbf{XIsin}\varphi=\mathbf{Ecos}\delta - \boldsymbol{V}, \boldsymbol{thus}$

$$\mathbf{Isin}\varphi = \frac{\boldsymbol{E}}{\boldsymbol{X}}\mathbf{cos}\delta - \frac{\boldsymbol{V}}{\boldsymbol{X}} \tag{6}$$

Since, the active power P = VI cos ϕ, thus from the equation of | BC= the active power as $P = \frac{EV}{X}$ sin δ. As the voltage of buses of the power system should be maintained within specified limits, the active power (P) is strongly related to the power angle (δ) variation and this angle should be maintained within the limits (solid line in the P(δ) characteristics in Fig. 8.b. Otherwise the stability of networks and frequency will be affected.

The synchronism of the system may be lost at high integration of variable RESs due to a sudden large change in active power supply/demand. Occasionally, cascade events occurrence take place, resulting in a blackout. An illustrative case is the South Australia blackout incident that happened in September 2016 (Xu et al., 2023a). The extreme weather conditions triggered a chain reaction of

failures across the entire South Australian power grid. This included the disconnection of three transmission lines, the shutdown of more than half of the wind power generation capacity due to protective measures (approximately 25 % of the total state-wide electricity production), and the isolation of South Australia from the broader Australian power network due to the overflow protection mechanism of the Haywood interconnector. These events ultimately resulted in a collapse of the system's frequency and a widespread power outage across the state,

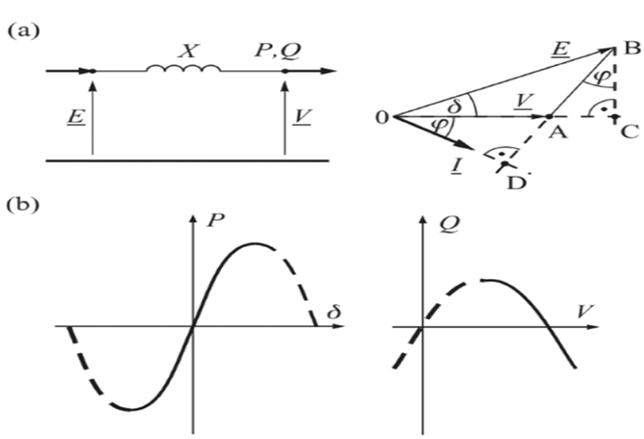

Fig. 8. A simplified representation circuit: (a) circuit and phasor diagram, (b) Active power and power angle, Reactive power and voltage (Prabhakar et al., 2022).

stemming from a significant imbalance between the remaining electricity generation capacity and the electricity demand.

Another instance was the power outage incident that occurred in the United Kingdom in August 2019. This blackout incident had a substantial impact on millions of energy consumers, disrupting approximately 1 (GW) of electricity demand, constituting about 5 % of the country's overall consumption. The total generation loss surpassed the available backup reserves, prompting the implementation of mandatory demand response measures to restore and stabilize the system's frequency (Prabhakar et al., 2022).

Maintaining the equilibrium between supply and demand, regardless of the system's sufficiency, should be the goal of stability control and regulations to prevent these cascading events. Over the world, different standards and regulations have been announced including under and overvoltage events, which might arise with disturbances with the integrating power plants as shown in Table 4. For example, according to the Danish Grid regulation, grid-connected wind and PV systems are obliged to remain connected and operational for a duration of half a second when there is an 80 % drop in voltage at the Point of Common Coupling (PCC). If the voltage at the PCC recovers to reach 90 % of its original level within 1.5 seconds, the renewable power plants will continue to function without undergoing a disconnection. However, if this voltage recovery does not occur, disconnection becomes mandatory.

Due to the potential for voltage surges (High-Voltage Ride through, HVRT) to create overvoltage issues in the electrical grid and subsequently destabilize voltage levels, modern integration regulations now mandate that renewable power plants maintain their connection to the utility grid when voltage levels rise for a specified duration. This measure is implemented to ensure the stability of the voltage (Al-Shetwi et al., 2020).

4.3. Reactive power (Q) injection/absorption

From the basic formula of the reactive power of single-phase circuits Q = V I sin ϕ, and phasor Eq. 6 the relationships between the Q and voltage can be simplified as

$$\boldsymbol{Q} = \frac{\boldsymbol{EV}}{\boldsymbol{X}}\mathbf{cos}\delta - \frac{\boldsymbol{V}^2}{\boldsymbol{X}}, \mathbf{Sine}, \ \mathbf{cos}\delta = \sqrt{\mathbf{1} - \mathbf{sin}^2\delta} \tag{7}$$

Then,

$$\boldsymbol{Q} = \sqrt{\left(\frac{\boldsymbol{EV}}{\boldsymbol{X}}\right)^2 \quad - \boldsymbol{P}^2 - \frac{\boldsymbol{V}^2}{\boldsymbol{X}}} \tag{8}$$

This equation shows the strong relation between Q and V, and Q is often required to maintain the voltage stability of the electrical grid. The grid should be operated within acceptable limits of Q as shown by the solid line in Fig. 8.b of Q (V).

In the case of RES integration, RESs produce less reactive power compared with traditional generators. With the deployment of RESs and the expansion of power transmission, there is a greater demand for reactive power to sustain system voltage levels. Reactive power deficits lead to violations of dynamic stability regulations, requiring load dispatch or RES curtailment (Thiesen et al., 2016). Load dispatch can be

Table 4
Standards and regulations of voltage ride through.

Country Reg.	Low voltage ride-through LVRT				High-voltage ride through HVRT	
	during fault		post fault		during fault	
	Vmin. (%)	tmx. (s)	Vmx. (%)	Tmx (s)	Vmx. (%)	Tmx. (s)
Denmark	20	0.5	90	1.5	120	0.1
USA-NERC	15	.625	90	3	120	1.0
China	20	.625	90	2.0	-	-

done by managing, controlling, coordinating and optimizing the output of diverse power generation sources within the grid. Additionally, RES curtailment is a modification and intentional reduction of the RES output by grid operators to meet the demand. For example, wind power plants may need to provide or absorb reactive power to ensure that the voltage remains within acceptable limits by using the control devices of power electronic converters of a doubly-fed induction generator (DFIG) drive system.

Due to the nonlinear system of reactive power generated /demand, it is essential to optimize Q dispatch. Artificial Intelligence (AI) and optimization techniques can be used to solve this optimization problem to find the optimal settings of the control variables, such as the buses' voltage magnitudes, transformer tap settings, and reactive power VAR values of the system voltages. The primary objective is to reduce power losses while simultaneously ensuring that the operational constraints of the power network are upheld (Jamal et al., 2023). Reactive power management of PVs and wind turbines' takes special attention from research and industry as their growth share in the energy mix has dramatically increased in the last decade.

However, this integration at a large scale without active management (Mehbodniya et al., 2022) threatens the voltage stability of the system due to its limitation of reactive power Q generation; that is why the Optimal Reactive Power Dispatch approach (ORPD) is key to improving the voltage stability of the electrical power network reducing the power losses and providing economical operation. For this approach, a mathematical model of the ORPD problem is required, which involves defining the objective function and the constraints of the problem. To solve the ORPD problem, the authors of (Jamal et al., 2023) presented a modified version of the Artificial Hummingbird Algorithm (MAHA). Two significant changes have been made to this improved algorithm: Levy's Flight Distribution is integrated, and the hummingbirds' distance bandwidth movements towards the global solution have been adjusted. These modifications greatly increase the algorithm's potential for exploration and exploitation, which successfully addresses problems associated with entrapment and stagnation. Additionally, a stochastic ORPD approach was proposed, accounting for uncertainties in RESs like solar, wind, and hydropower. This inclusion aims to boost the efficiency and reliability of solving the ORPD problem. The authors concluded that their proposed MAHA algorithm surpasses other optimization techniques in both convergence speed and the quality of solutions. Deploying Flexible AC Transmission System (FACTS) devices such as Static Synchronous Compensators (STATCOMs) to provide dynamic reactive power support, ensuring voltage stability during RES variability or faults. Incorporating capacitor banks at critical grid nodes to enhance reactive power availability and maintain voltage levels.

4.4. Decreasing short-circuit level

The Short-circuit level determines the system's capacity to supply power in the event of a failure. When short-circuit levels are high, faults clear quickly, effectively, and with the minimum extent of disturbance to the system reasonably possible, thus, it is a crucial property of power systems. Energy shifting to RESs reduces a power short-circuit level, potentially causing equipment failure or tripping. Consequently, such a shift makes fault identification more difficult and increases voltage instability. Solar PV and wind turbines are usually linked to the power supply at lower Voltage (distribution network) levels through the power electronic (PE) interface as shown in Fig. 9. Comparing this PE-interfaced system to the conventional synchronous generators in power systems reveals that the former has greater fault contribution, and PE-interfaced systems do not produce higher short-circuit currents in the event of a fault. The study (Aljarrah et al., 2023) proposes three approaches to address fault level deficits: introducing synchronous condensers and maximizing the transient overrating and fault-ride-through (FRT) capacity of PE converters-interfaced RESs. While installing synchronous condensers is costly, it yields the most substantial fault level improvement. Enhancing transient overrating significantly improves fault levels, but it requires pricier converters. Maximizing FRT capabilities is a cost-effective solution without additional hardware; however, it might not completely alleviate deficits in grids with high-RES penetration. Optimizing converter interface overrating, resulting in a 35.8 % average fault level increase, is the recommended course of action.

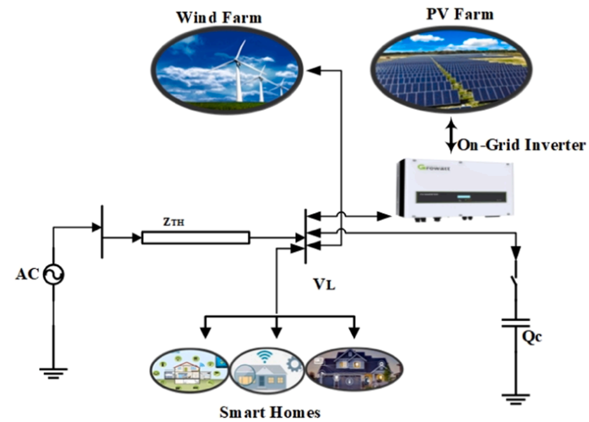

Fig. 9. Single line diagram of integration of RESs and capacitor bank.

Grid operators can take actions such as changing the settings on existing equipment to increase the system's short-circuit power. Limiting the amount of RES production that may be connected to the system at lower voltage levels is another tactic to mitigate the impact of RESs on short-circuit power. Nevertheless, these actions can be expensive and need large expenditures for new infrastructure or equipment. Additionally, Capacitor banks are often utilized close to the load centre at both the transmission and distribution levels to sustain voltage under heavy loads as shown in Fig. 9. The extent of the voltage step change is contingent on the power system's robustness at the point of connection, which is defined by the fault level. The greater fault level reduces voltage fluctuations caused by the switching of capacitor banks. Consequently, a minimum fault level is required to guarantee that the voltage remains within the specified limits following a switching event.

$$\Delta V\ \% = (MVAc/MVAsc) \times 100 \tag{9}$$

Here, MVAc and MVAsc are capacitor bank rating and fault level respectively. The minimum fault level equivalent to 10 times the rating of the switched capacitor bank is required. In other words, MVAsc $<$ MVAc to prevent going beyond the voltage limitations (Aljarrah et al., 2023).

5. Electric vehicles and power system stability

As countries keep developing and expanding their automation, transportation, infrastructure, and technology, significant harmful pollutants are released into the environment. In addition to industrial pollutants, automobile emissions contribute significantly to the atmospheric release of GHGs, which intensifies global warming and causes climate change (Saber and Venayagamoorthy, 2010).

In the European Union, transport is the second-biggest source of atmospheric GHGs. Global data on GHG emissions show that production (21 %), transportation (27 %), and energy generation (29 %) were the primary contributors to global GHG emissions in 2015 (Aminzadegan et al., 2022). Consequently, using EVs in the transportation sector should be part of the overall transition. Moreover, as fossil fuel reserves deplete, their costs continue to increase- especially after a conflict between Russia and Ukraine. From this point of view, one effective solution to mitigate this situation is to shift to EVs. Plug-in hybrid electric vehicles (PHEVs) are expected to become increasingly widespread (Fang et al., 2011). By 2040, half of all cars on the road will be electric (Sharma and Jain, 2020). In addition to solving environmental issues, especially those related to GHG emissions, EVs also make it easier for RESs to be integrated into power systems, which helps mitigate power system stability issues by using their energy storage system. EVs can serve as self-dependent distributed energy resources within the electrical utility grid, offering supplementary services including minimizing peak power demand, supplying spinning reserves, and assisting in voltage and frequency regulation. Using intelligent charging solutions and the strategic utilization of existing infrastructure, alongside the installation of a well-considered network of RESs for future charging facilities. Charge management may be carried out with precision and can effectively alleviate the consequences of EVs charging on the power grid, ensuring minimal disruption to the overall load (Barman et al., 2023).

According to charging and discharging, the EV integration paradigm may be classified as Grid-to-Vehicle (G2V) and vehicle-to-grid (V2G), as shown in Fig. 10. The EV integration with the grid can have a significant effect on the energy economy, system stability, and power dependability (Tavakoli et al., 2020). For example, in the G2V scheme, in the load shifting scheme, at off-peak hours EVs allow charging when there is excess power generation capacity on the grid (or higher generation of RESs), which may threaten the power system stability by increasing the voltage and frequency of the grid. This charging is considered a burden on the grid and helps to avoid voltage fluctuations and overloading of transmission and distribution lines. EVs may adjust their charging rates in response to grid frequency variations and help stabilize the grid during periods of high-RES generation or low demand, this system is like Voltage Regulation and Frequency Support. This load shifting not only alleviates congestion and prolongs the lifespan of transformers but also decreases the reliance on expensive power plants during peak periods, thereby improving the economic efficiency of the grid (Sharma and Jain, 2020).

However, as EVs charge from the grid, they act as non-linear loads with distinct characteristics compared to typical loads, potentially exerting a burden on the network. Additionally, uncertainties related to the locations, timing, and duration of EV charging introduce challenges in forecasting the behaviour of this novel load. Consequently, a large amount of EV charging might cause concerns about power system stability (Tavakoli et al., 2020) in the case of their stochastic charging. In other words, the uncoordinated charging of a significant number of EVs simultaneously can result in grid instability and a surge in peak demand. To address this, an Electric Vehicle Aggregator (EVA) can implement organized and distributed charging/discharging rates for EVs throughout the connection hours, thereby offering grid stability and regulatory support to the system operator (Sharma and Jain, 2020). This scheduling process is conditioned on both grid-related and EV constraints. EVA devises hourly schedules for EVs charging at an optimal rate, referred to as the Preferred Operating Point, which represents the desired average power consumption level for the EVs (Bessa and Matos, 2012). According to Xu et al. (2023b), EVA collects a significant amount of EVs in a regulated location. The EVA can supervise, arrange and optimize the plugging and unplugging of these EVs as a single unit due to this aggregation. The total number of EVs in the power market is characterised by EVA. Based on the combined capacities of the managed EVs, it bids and offers electricity. Maximising EVA's advantages-such as cost reductions and income generation is the goal. Overall, EVA acts as an intermediary between EV users and the electricity market, aggregating EVs, optimizing their operations, engaging in market activities, providing grid services, and ensuring a mutually beneficial arrangement for all stakeholders.

Demand response (DR) offers the flexibility to choose a suitable charging time based on the available plug-in duration and the initial State of the Charge (SoC) of the EVA. However, to fully unlock the potential of DR, it is crucial to establish the pricing dynamics provided to EV owners, encouraging their active participation. In addition, combining time-of-use (ToU) pricing with a DR strategy can offer added motivations for load-shifting (Hurlbut et al., 2019). Utilizing DR, overnight charging of EVs can be strategically spread across periods when the energy cost is lower, resulting in a more consistent daily load profile. In other words, Valley filling involves raising load consumption by EVs charging to level out the load curve (Abdullah-Al-Nahid et al., 2022).

On the other hand, unregulated EV charging can create a new peak during the valley hours and overburden the network (Qian et al., 2010). In unidirectional V2G systems, the EV's battery is regarded as an adjustable load used for grid power balancing. Since an EV's battery is small, it has a negligible effect on grid stability. However, with the

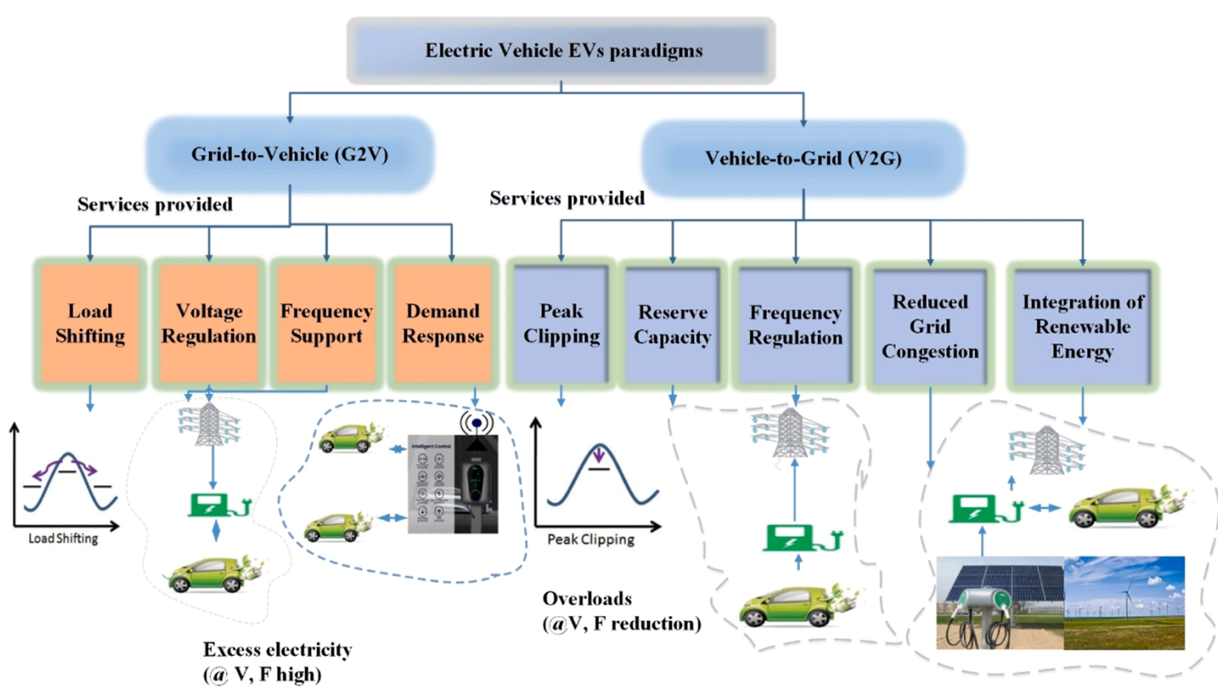

Fig. 10. Electric Vehicle paradigms.

penetration of a substantial number of EVs, the impact is prominent, to address this, again an EVA is inevitable to serve as an intermediary between individual EVs and the market operator. The EVs have the option to link with a third-party aggregator either independently or collectively as a fleet operator, such as a citywide parking facility (Tavakoli et al., 2020). It is important to recognize that within the Smart Grid (SG) context, the EV paradigms (i.e. G2V and V2G) are interrelated. For instance, the EVs are frequently employed both for "Peak Clipping" (supplying power to the grid during high-demand periods) and "valley filling" (charging during low-demand times). Consequently, one of the most important factors to consider is when and where to charge and discharge during the day (Fang et al., 2011). These paradigms of two-way capable (Bidirectional) EVs show great promise within the power systems sector. Power distribution companies can leverage these versatile EVs as valuable assets to address operational challenges, including contingencies, peak load reduction, and voltage regulation (Kazemtarghi et al., 2022). Depending on their design, bidirectional EVs can serve in G2V mode as consumers of electricity and in V2G mode as decentralized power generators (Yuan et al., 2021).

5.1. Integration of electric vehicles in demand response programs for ancillary services

Electric Vehicles (EVs) are a potential and coveted distributed load reacted to DR with the idea to aggregate ancillary services (e.g. frequency and voltage support) essential for system operation and stability. As an increasing population of flexible, energy storage assets, EVs can serve as another tool for grid-operating entities tasked with ensuring that system remains stable, especially in high-renewable-penetration scenarios, when generation can be variable. Perhaps the most interesting use case for grid services using EVs is V2G (Vehicle-to-Grid) programs. When they are available in a region with an appropriate system in place, V2G allows EVs to discharge electricity back to the grid, aiding description through the frequency through responding to imbalances in supply and demand. This is especially valuable in times where RES generation exceeds demand, allowing the extra provided energy to be stored in the batteries of vehicles or in times where RES generation is deficient, where a supplementary supply of energy is needed. For example, grid operators can aggregate fleets of small-scale EVs and tap into this form of large-scale storage to utilize for services such as spinning reserves and voltage support (Goudarzi et al., 2022)

EVs can also help improve voltage stability through the provision of reactive power support. High penetration of EVs can allow fleets of electric vehicles to provide reactive power compensation, absorbing or supplying reactive power to self-regulate voltage within limits. Smart charging systems enable collaboration with demand-side management (DSM) technologies, which can help reshape when EV charging occurs in order to coincide with lower demand or times when more RES are being generated. In this sense, smart charging systems provide peak shaving functionalities and reduce stress on the grid. But there're a range of technical and regulatory issues that need to be worked through to enable the full optimization of their coordination in DR programs (Guerrero et al., 2010).

5.2. Technical challenges

To enable effective coordination between EVs and the grid, robust communication systems are required. To enable grid operators to manage EV charging and discharging according to grid conditions, smart charging infrastructure with data exchange capabilities in real-time must be deployed. It needs diverse entities to engage in such a process, and to have interoperability between vehicles, charging points and grid operators. If EV batteries are cycled frequently (charged and discharged for services rendering) they can also degrade faster than they would otherwise, and become life limited. Optimized algorithms for battery management that balance grid service provision with energy storage longevity must be developed to ensure that EVs can provide demand response services without damaging battery life. In addition to that, EVs need to have advanced power electronics and inverters to provide frequency regulation and voltage support to the grid by responding to the grid frequency and voltage dynamics. Therefore, these systems will need to be integrated with the associated grid control mechanisms to ensure fast and reliable operation (Waseem et al., 2020a).

5.3. Regulatory challenges

Regulatory frameworks that ensure reliable and fair compensation in DR programs will encourage EV owners to engage in such programs. EV owners must be compensated for their vehicle batteries being utilized as an asset to supply grid services. That said, a fair and sustainable compensation model — one that takes into account both the benefits to the grid and the cost to the owner of the vehicle — is one of several complex regulatory questions that must be balanced. In certain regions, grid operators may lack the regulatory capability to mandate EV involvement in ancillary services markets. Policymakers need to set standards for grid access — the grid should be stable enough for EVs to contribute services without risk of destabilizing the grid. It may include revisions to grid codes to enable EV charging stations to participate in ancillary service markets just like any other resource. In low EV penetration areas, the capacity to implement large-scale DR programs may be constrained. Policy is one way to create incentives for Electric Vehicle adoption (as well as the installation of smart charging infrastructure): rebates, tax breaks, and EV related subsidies will all help get EVs into more hands. Local regulatory frameworks also need to ensure that achieving balance in EV integration vis-à-vis grid services does not disadvantage regions with low levels of EV adoption (Liaqat et al., 2021).

In regions with low EV penetration EV pilot projects are the way to go initially to test V2G in a controlled environment to show the value to the grid and ecosystem. They can lay out a regulatory framework, develop technical standards and show the business case for broad participation of EVs in grid services. As EV penetration increases over time, the coordination between EVs and grid operators can evolve in sophistication, with increased dependence on artificial intelligence (AI) and machine learning (ML) to estimate EV availability and optimize charging and discharging schedules. Electric mobility integration in demand response programs adds substantial potential for electrical vehicles to act as a distributed load resource to provide ancillary services (for example, frequency and voltage support). However, streamlining this integration involves technical challenges in communication, battery management, and grid control systems, as well as regulatory hurdles concerning access to the grid, compensation models, and market participation. Through appropriate incentives, clear regulatory frameworks, and the ongoing development of smart grid technologies, EVs will be a critical element of more stable grid solutions that make a renewable energy future feasible (Rizwan et al., 2020).

6. Methods, tools, and software for power system stability analysis

The new electric network paradigm consists of an extensive array of elements that make the system and network complicated from the point of view of study, control, and operation of power system stability. Conventional power system calculation approaches are complex and, at times, unfeasible due to the time-consuming calculations required by the big data system. The calculation result is necessary to understand, predict, optimize, assess the risk of, regulate, design, test and validate power system functioning. Using advanced computer programs and simulations have become essential in power system stability studies. Using state-of-the-art instruments, engineers and researchers may investigate the complex dynamics of power systems, including grid integration, fault analysis, and transient stability. This section takes us on an overview of some of the most well-known and extensively used software designed to address specific aspects of power system stability analysis. With these crucial instruments and software, we can thoroughly examine the behaviour of power systems in a constantly changing energy environment.

Fig. 11 shows the software and techniques which can be used for Power System Stability Analysis.

6.1. Artificial Intelligence (AI)

The domain of artificial intelligence (AI) encompasses the broader field of machine learning, within which deep learning serves as a specific, though progressively significant, component. Reinforcement learning (RL), on the other hand, stands as a distinct subfield within machine learning, featuring its distinctive approach to model training. The authors of Sarajcev et al. (2022) reviewed the state-of-the-art methods in the application of AI to power system transient stability evaluation, emphasizing various machine learning approaches. Model building and training (including ensembles and hyperparameter optimization techniques), data generation processes (from measurements and simulations), data processing pipelines (features engineering, splitting strategy, and dimensionality reduction), deployment, and management (with monitoring for detecting bias and drift) are all covered in the review. The authors of Boza and Evgeniou (2021) underscore that the substantial integration expenses associated with Variable Renewable Energy (VRE) pose a significant burden to their widespread adoption. They examined how AI could potentially mitigate the costs of their integration into the power system. They discussed that AI solutions and data-driven technologies hold considerable promise in effectively managing these expenses, adding substantial value to the system. Nonetheless, uncertainties and a lack of comprehensive understanding regarding AI's impact frequently deter decision-makers from committing to investing in AI and data-centric technologies within the energy sector. Conclusively, the authors affirm that AI presents favourable avenues to bolster VRE integration by mitigating the integration costs. This potential encompasses various aspects, including enhancing the generation (Voyant et al., 2017), and demand (Raza and Khosravi, 2015) forecasting, fostering more efficient balancing of markets (Santos et al., 2015), and optimizing energy resource dispatch. However, the adoption of AI solutions faces obstacles arising from various factors inherent in the power sector, such as susceptibility to cyberattacks, privacy concerns, and the complexities linked with the existing data infrastructure. The authors of Wang et al. (2022) introduce a unique approach for transient stability evaluation and stability region determination based on Lyapunov functions and artificial intelligence (AI). The authors use neural networks as generic function approximators to generate Lyapunov functions, which are then optimized using stochastic gradient descent (SGD). The approach contains a falsifier that detects state vectors that violate Lyapunov stability criteria, which are subsequently utilized to improve the training set and speed up convergence. This approach's efficacy is proven with the IEEE 9-bus 3-machine system. However, this approach has difficulties like the falsifier discovers state vectors that violate stability criteria, therefore the Counterexamples have been added to the training set to accelerate convergence. The authors of Alqahtani et al. (2023) investigate the application of intelligent strategies to improve the stability, control, and protection of power systems. As energy needs rise and renewable energy sources become more integrated, ensuring stability and dependability in both traditional and smart grids becomes more difficult. The study addresses sophisticated approaches including artificial intelligence, deep learning, machine learning, metaheuristic optimization, fuzzy logic, reinforcement learning, and model predictive control. These techniques are critical in predictive maintenance, fault detection, real-time control, and monitoring. The study emphasizes the efficacy of AI and machine learning in improving protection systems and investigates the possibilities of fuzzy logic and reinforcement learning for decision-making and dynamic stability control. It also looks at the use of IoT and big data analytics for real-time monitoring and optimization.

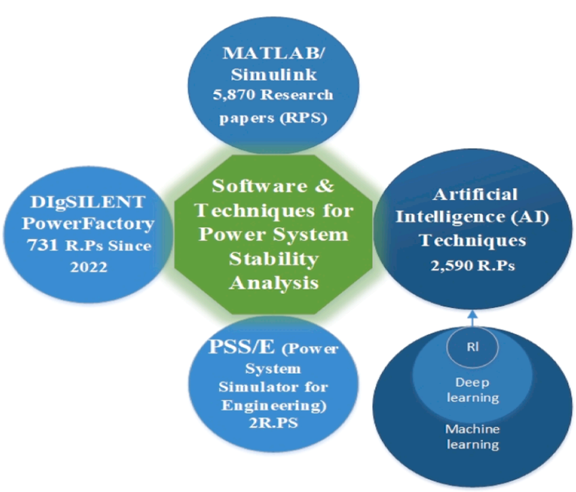

Fig. 11. Power System Stability Analysis Tools.

To sum up, the complexity of today's electricity grid necessitates similarly sophisticated instruments and solutions. As a result, Artificial Intelligence (AI) can be used to manage large datasets for a variety of analytical tasks, such as demand forecasting, generation prediction, maintenance planning, and real-time monitoring and control.

6.2. MATLAB/Simulink

MATLAB is a useful and flexible computing environment tool for studying power system stability. Engineers and researchers are specifically able to simulate sophisticated electricity grids, complete with generators, transmission lines, and control systems, because of the toolbox that Simulink provides. To investigate transient stability, fault responses, the effects of RESs integration, and dynamic simulations based on this modelling are used. The computational capabilities of MATLAB facilitate control strategy and system configuration optimization. Assisting in the identification and resolution of stability concerns, it allows the analysis of grid performance under various circumstances. Proposing solutions and evaluating data are simple by the user-friendly interface, which simplifies result visualization. Here, we provide an overview of some of the latest literature reviews used in power system stability analysis by examining the real-world applications of MATLAB and Simulink.

The authors of Niu et al. (2022) examine the frequency stability of the electricity grid in the Kingdom of Saudi Arabia (KSA) and provided insights into the evolving energy dynamics within the KSA grid. The investigation focuses on understanding how the increased integration of inverter-fed RESs influences the dynamic behaviour of the KSA grid. The analysis of RESs' impact is carried out through simulations using MATLAB/Simulink simulation software that explores potential future scenarios of the KSA power system. These simulations are conducted using the MATLAB/Simulink simulation software. The objective is to assess how the growing presence of RESs may affect the overall stability and performance of the KSA grid. Simulation findings reveal that increased penetration of RESs significantly impacts the system's frequency response, particularly during off peak periods. Additionally, the results highlight how aggregated Battery Energy Storage Systems effectively improve the frequency control within the KSA grid.

In Kapse et al. (2023), authors used MATLAB to introduce a quantitative approach for assessing the influence of RESs integration on transient voltage stability. Leveraging input-to-state stability theory, the research formulates security and stability metrics to appraise the system's stability attributes. The findings reveal that as the share of RESs rises in the range of 35–95 % and power flow transferring as 10 %, the quantitative stability index λ consistently declines; as RESs reach an 85 % share, the quantitative security index μ turns negative; signifying that the voltage at the wind farm surpasses operational limits. This is considered the critical increasing limit for the penetration of RESs with no violation of power system stability. The simulation outcomes reveal that when there is a substantial integration of inverter-coupled RESs, it significantly impacts the system's frequency response. The Rate of Change of Frequency becomes more noticeable, and the system frequency rapidly declines to levels that are deemed unacceptable. This situation leads to undesirable Under-Frequency Load Shedding and a cascading failure in the generation. The most adverse frequency response is observed under conditions of high RES penetration during base load scenarios, primarily due to the significant reduction in the overall system's inertia.

In Wang and Milanović (2023), the authors developed wind turbines of DFIG and Squirrel Cage Induction Generator (SCIG) models, which are integrated into an adapted IEEE 14-bus power system. This study predominantly focused on the assessment of voltage stability through the examination of angular stability to identify a Critical Clearing Time. This was achieved by investigating the responses of the test system's synchronous generators to parameter variations during three-phase fault conditions by applying the Power System Analysis Toolbox (PSAT) MATLAB toolbox. The results show that DFIG exhibits superior performance compared to the SCIG model, and the choice of generator technology significantly influences transient stability.

6.3. DIgSILENT PowerFactory

The name DIgSILENT stands for "Digital Simulation and Electrical Network Calculation Program. For over three decades, DIgSILENT has been at the forefront, establishing

benchmarks and influencing trends in the modelling, analysis, and simulation of power systems. The PowerFactory software has consistently demonstrated its advantages, characterized by comprehensive functional integration, extensive modelling and analysis features spanning generation, transmission, distribution, industrial networks, and robust data management tools ensuring data consistency and traceability, ultimately boosting overall work efficiency. The latest version, PowerFactory 2024, introduces an improved user experience through enhancements to the user interface and additional data handling tools and many examples and case studies. It also introduces new functionalities and expanded modelling capabilities designed to support network planning and operations.

The authors of (Boričić et al., 2021) discussed the challenges of modern power systems due to the integration of RESs and the decommissioning of traditional synchronous generations. They addressed these challenges and introduced a new probabilistic framework and two composite stability indices that can assess multiple aspects of power system stability simultaneously. The proposed framework and indices are flexible and can be applied to other power system analyses and even studies beyond the power system. They demonstrated the application of the indices in case studies with modified IEEE 9- bus and modified IEEE 68-bus test systems without/with RESs in a mixed MATLAB and DigSilent Power Factory simulation environment. The results show that the proposed framework and indices can effectively assess multiple aspects of power system stability and help avoid decisions that could endanger system stability.

In Dharmakeerthi et al. (2014), the researcher uses Python scripting in DIgSILENT Power Factory 2020 SP2 software to solve this problem of complexity and multitude of variables, enabling flexible and user-specific functions as well as improved parameter evaluation for the dynamics of the system. To determine the relationship between different distribution system details and the bulk power system short-term voltage stability (STVS), the research employs sophisticated load and Distributed Energy Resources models in a large-system investigation. They categorically state in their study's conclusion that DER units and dynamic load are crucial to distribution-transmission interactions. While DER units are shown to be either advantageous or detrimental, depending on various parameters like control techniques and fault-induced delayed voltage recovery (FIDVR), it has been demonstrated what amounts and compositions of dynamic loads are the most destructive to the STVS. It is anticipated that dynamic load presence and DER penetration will rise quickly due to the power systems' present strategic direction towards low-emission greenhouse gas emissions, which might threaten short-term voltage stability.

7. Solutions and technologies

In the previous sections, we considered the impact of the high-scale integration of RESs and EVs into the grid. We deduce that the high integration of these non-dispatchable sources threatens the stability of the power system. Additionally, this integration may lead to subsequent events of failure or blackouts. Due to the non-dispatchable characteristics of these sources and a decrease

in the system inertia, the network could be rendered more vulnerable to major disturbances that have the potential to trigger an extensive blackout (Ódor et al., 2023). Both power system operators and customers may suffer serious consequences as a result of such events and grid blackouts. The magnitude of these effects may differ based on the extent of the malfunction and the efficiency of the countermeasures. Power system operators will face operational challenges to recover power after the blackout, and they have to manage grid operations, arrange repairs and maintenance, and collaborate with numerous stakeholders to restore electricity as soon and securely as possible. After a blackout, restoring the electricity grid is a systematic and complicated procedure that calls for several considerations and actions. The goals of the recovery procedure are to guarantee grid stability, provide electricity back to impacted areas, and stop future occurrences of these kinds of events. In addition, due to the disruption of customers' daily activities, financial businesses, and healthcare, the customers will complain about the utility's service since they are unaware of what is happening. From this point of view and for several reasons, including the influence on the economy, national security, public safety, and even consequences such as disrupting transportation networks, it is crucial to control cascading failures on power grids to avoid failures before it is bound to happen (Numan et al., 2023). Therefore, the power system operators ought to utilize various technologies and solutions to prevent this situation as much as possible. This section introduces cutting-edge technologies and solutions to mitigate power system stability.

7.1. Energy Storage Systems (ESSs)

In systems with abundant RESs, it is difficult to maintain the balance between generation and demand (Impram et al., 2020); and this imbalance directly affects the flexibility criteria (Wong et al., 2019). ESSs are essential for mitigating this imbalance issue. The advantages of ESSs in power systems, particularly with the integration of RESs, are undeniable (Kumar and Palanisamy, 2020). Their integration plays a vital role in capturing excess energy during periods of high generation and releasing it during peak demand. It offers controllable capabilities to provide ancillary services (Saber and Venayagamoorthy, 2010), (Akram et al., 2020), frequency support (Pengfei et al., 2023), voltage regulation (Giarola et al., 2021), time shifting, and even the ability to initiate a power system after a blackout (Luo et al., 2015). The growing demand for ESSs has motivated continuous efforts to explore more efficient methods that satisfy specific requirements. ESSs can be categorized based on their intended purpose, response time, storage duration, the type of stored energy, and other factors requirements (Zhao et al., 2022a). Various energy storage techniques can store and release electrical, thermal, or mechanical energy, offering versatility and stability to the power system (Díaz-González et al., 2016).

Fig. 12 illustrates the categorization of ESSs according to the type of stored energy (Al Kez et al., 2022). In the smart grid, ESSs may be applied extensively, spanning from electricity generation to consumer usage. ESSs manifest in diverse forms, including bulk storage systems designed for prolonged energy retention, such as pumped hydro energy storage. Furthermore, ESSs can take the form of residential storage systems, addressing shorter-term energy requirements, typically extending for hours. ESSs can be used for grid voltage stability enhancement, power grid reliability, power quality improvement, renewable support, and grid energy management, improvement of grid frequency excursion suppression, grid angular stability enhancement, and customer energy management.

Table 5 provides a concise overview of the techno-economic characteristics of these energy storage technologies (Hossain et al., 2020), (Rehman et al., 2015). Compressed Air Energy Storage (CAES): CAES supports large-scale applications with capacities of 3–1000 MW and discharge durations of up to 24 hours. Its efficiency ranges from 70–90 %, and its cost is moderate ($2–200/kWh). CAES excels in seasonal storage but is limited by the need for geological formations for air storage. Its integration with fossil fuels in traditional systems poses environmental concerns, although advancements are moving towards renewable-integrated CAES systems. Flywheel Energy Storage (FES): FES stores energy in the form of rotational kinetic energy. It provides rapid response times (milliseconds to seconds) and high-power density, making it suitable for frequency regulation and power quality improvement. FES has a moderate lifespan (15–20 years) and efficiencies of 70–93 %. However, its energy density is low, limiting its use to short-duration applications. It is often used for ancillary services in microgrids or urban power systems. Hydrogen Energy Storage (HES): HES

electrolyze, providing one method of hydrogen storage, then convert hydrogen back to electrical energy using fuel cells or turbines. The solution provides high energy density (500–3000 Wh/L) and scalability, making it a long-term, large-scale storage option. HES could be combined with RESs to enable long-duration energy storage capability. But, it is very inefficient (20–50 %) due to conversion losses and needs a lot of infrastructure (NG pipeline). However, the versatility and potential of hydrogen as a zero-emission energy carrier make hydrogen a promising technology for future energy systems despite these challenges. With high scalability and flexibility and rapid response times (milliseconds to seconds), BESS is well-suited for applications such as frequency regulation, voltage stabilization, and peak shaving. It has a very high energy density compared to alternatives (95–500 Wh/L with efficiencies of (85–98 % li-ion)). Nonetheless, the price ($120–1000 / kWh) and short lifetime (5–15 years) due to cell degradation are a limitation. With those aside, BESS is being adopted more often than ever in distributed energy systems and urban grids for the reason of its versatility and capability to react to the immediate need of the grid. Supercapacitors (SC): SCs store energy electrostatically and have very high-power density, very fast response time (milliseconds). Which are suitable for voltage stabilization and short-term power compensation. SCs exhibit high efficiency (90–95 %) and long lifespans (over 20 years). However, their low energy density makes them unsuitable for long-duration storage, limiting their application to grid-support functions such as smoothing voltage fluctuations and bridging short power gaps.

Pumped Hydro Energy Storage (PHES): PHES is a well-established technology suitable for large-scale, long-duration storage. It offers high energy capacities (up to 5000 MW) and long lifespans (40–60 years). With moderate efficiency (70–85 %), it is cost-effective ($5–100/kWh) and ideal for load balancing, peak shaving, and seasonal storage. However, PHES is geographically constrained and requires significant initial investment and construction time. Its application is optimal in areas with suitable topographical features such as reservoirs. Due to PHES's simplicity and high-range energy storage capacity, it is the most widely utilized type of energy storage nowadays. PHES's capacity has reached 5000 MW with discharge time at rated power for a day (Rehman et al., 2015). On a global scale, PHES represents the most substantial energy storage capacity, accounting for approximately 95 %-99 % of the total energy storage systems. Its combined installed capacity exceeds 170 GW (Statista, 2023). Fig. 13 shows the installed PHES from 2010 to 2022 (IRENA, 2023) and the IRENA's global outlook for 2050 in (GW) (International Electrotechnical Commission, 2023). PHES technology offers numerous advantages to the energy sector, as it produces clean energy and has a minimal carbon footprint. PHES has significant potential for advancing the achievement of specific Sustainable Development Goal 7, aims to ensure access to inexpensive and sustainable energy as it is essential to growth in business, communications, agriculture, education, healthcare, and transportation (Diawuo and Amanor, 2023). When PHES is integrated with other RESs, it enhances the stability of the power system's transmission network and provides clean energy (Vasudevan et al., 2021). When there is an excess of power generation, such as an abundance of RESs, this surplus energy is employed to pump water into the upper reservoir. This stored energy can then be released during peak demand periods, reducing the overall production costs by avoiding expensive peak generation and promoting the utilization of cost-effective base load generation during periods of lower demand. This, in turn, contributes to load balancing and peak shaving, optimizing the power system's performance (Hino and Lejeune,

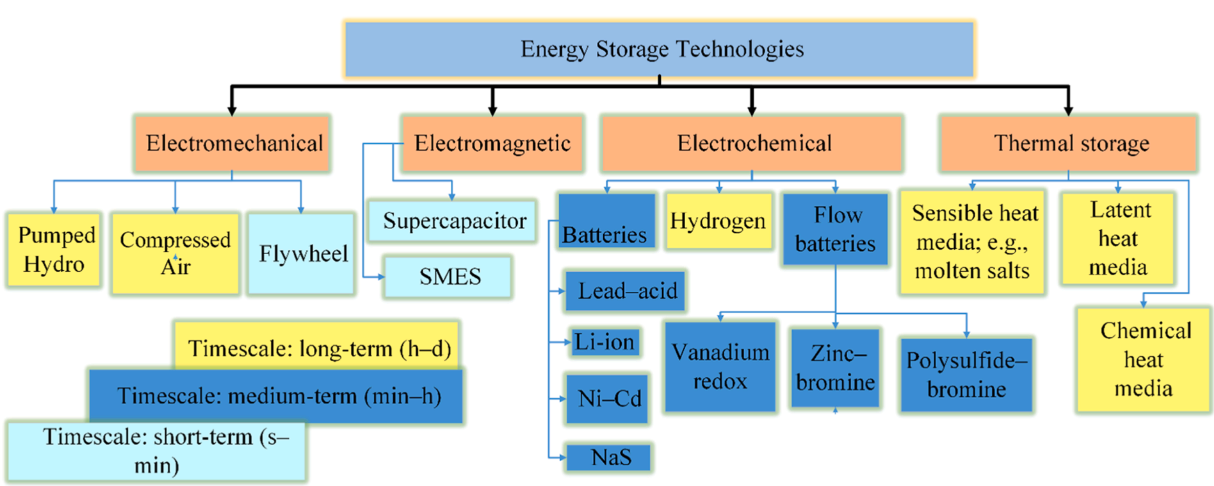

Fig. 12. Energy storage technologies.

Table 5
Techno-economic characteristics of the energy storage technologies.

Storage type	Capacity (MW)	Energy density (Wh/L)	Power density (W/L)	Efficiency (%)	Response time	Discharge Time at Rated Power	Lifetime (Year)	Capital cost($/kWh)
PHES	10–5000	0.5–2	0.5–1.5	70–85	s ~ min	1–24 h	40–60	5–100
CAES	3–1000	3–6	0.5–2	70–90	15 min	1–24 h (large CAES)	20–40	2–200
FES	0.1–0.25	20–80	1000–5000	70–93	4 ms	8s–15 min	15–20	900–12000
HES	0.1–50	500–3000	> 500	20–50	< 1 s	Seconds–24 h	5–15	10–20
Li-ion	1–100	95–500	56–800	85–98	ms ~s	Minutes–hours	5–16	120–1000
Lead acid	0–40	150–345	140–180	70–90	ms ~s	Seconds–hours	5–15	270–400
Flow cell	0.1–50	> 500	> 500	60–85	ms ~s	-	5–20	350–2000
SMES	0.1–10	0.2–2.5	1000–4000	90–98	10 ms	ms–30 min	> 20	10000
SCs	0.3–50	10–30	100000	90–95	10 ms	ms –1 h	> 20	20000
TES	0–300	80–500	-	30–60	10 ms	1–24 h	5–40	3–5

PHES pumped hydro energy storage, CAES compressed air energy storage, FES flywheel energy storage, HES hydrogen energy storage, Li-ion Lithium-ion battery, SMES superconducting magnetic energy storage, SCs Super-capacitor, TES thermal energy storage.

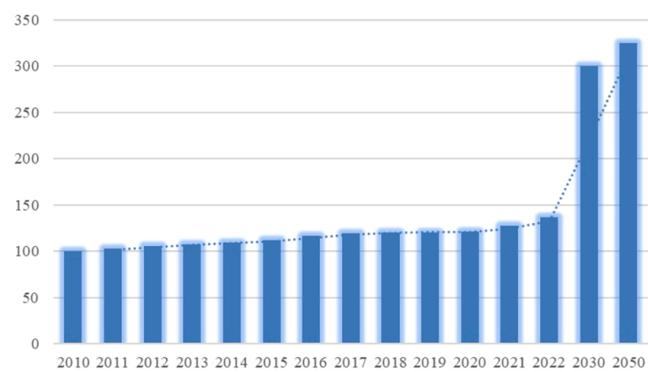

Fig. 13. Installed PHES and IRENA's global outlook (GW).

2012). Supplying power during the peak demand can also mitigate the reduction of the frequency and voltage. PHES can offer voltage control through the application of power electronics in variable-speed PHES plants. These systems can replicate the voltage control functionality of traditional generators. Alternatively, voltage control can be achieved through the use of conventional generators in fixed-speed and ternary PHES units (Das et al., 2021). Thus, PHES offers grid stabilization, voltage and frequency regulation, fast and flexible ramping, and even the black start (Vasudevan et al., 2021).

As per Table 5, PHES boasts the highest available energy capacity, ranging (1–5000 MW), whereas Li-ion battery storage technology exhibits a more limited availability, ranging from 1 to 100 MW (Hu et al., 2022a). PHES's characteristics are highly suitable for the effective integration of substantial variable, inverter-based wind and PV energy sources. PHESs exhibit a rapid response rate, transitioning from inactive to full output within 20 seconds to a few minutes. Moreover, a PHES contributes to rotational inertia, potentially compensating for the loss of rotational inertia associated with retiring traditional thermal generators. It also offers a black start capability, enabling the restart of an electricity system following a complete supply collapse without the need for an external power source to initiate the generators. The combined deployment of batteries and PHES has the potential to entirely replace the ancillary services historically provided by fossil and nuclear generators (Blakers et al., 2021). While the PHES has the potential to offer grid flexibility services by adapting its power output over time, it may experience operational stability challenges. When a pump begins and stops with frequent adjustments to output and changes in operation modes, a pressure spike known as the water hammer effect can occur in the pumping system. This effect causes unit vibration, flow noise, and load shedding, degrades the system's transient characteristics and produces negative damping for the total hydropower production, hence causing negative regulation (Feng et al., 2024). These problems not only reduce the lifespan of the units but also elevate the risk of failures and can exacerbate frequency variations (Zhao et al., 2022b). The primary reason behind the instability of PHESs lies in the disparity in response times between hydraulic parameters and electrical parameters, resulting in short-term energy imbalances (Keshan et al., 2016).

On the other hand, the substantial capital investment and geographical considerations pose significant challenges to PHES implementation (Statista, 2023), especially as it needs a reliable water source, such as a lake, a river, or other defined water supply (either salt or freshwater), to fill and maintain the reservoirs. Because of this, this technology is limited to usage in some nations with abundant water supplies. Also, other ES techniques can be integrated with RESs to improve power system stability. Table 6 summarizes the practical Energy Storage facilities and their utilizations, in reality, (Pengfei et al., 2023), (Zhao et al., 2022a).

ESSs provide a lot of advantages, but they also have drawbacks and difficulties. Below, the main drawbacks of ESSs are discussed.

A. *Lower energy density*: Energy density, expressed in kWh/L, is the quantity of energy that can be stored per unit volume of the storage medium (Keshan et al., 2016). As shown in Table 5, the highest energy density is 500–3000 for hydrogen energy storage. However, its capacity is in the range of 0.1–50 MW. The lower energy densities of ESSs indicate that to store the same amount of energy, they need

Table 6
Practical ESs facilities and impact on the system's stability worldwide.

ES Types	Location	Rating	Utilizations
Battery energy storage	Australia	30 MW/ 8 MWh	Fast frequency response.
	USA	8MW/2 MWh	Frequency regulation.
	Germany	8.5 MW/8.5 MWh	Frequency control and spinning reserve.
	Puerto Rico	20 MW/14 MWh	
	Japan	34 MW/ 244.8MWh	Wind power fluctuation mitigation.
	USA	10 MW/ 40MWh	Spinning reserve, load leveling.
	Ireland	2 MW/12 MWh	Wind power fluctuation mitigation
Superconducting Energy Storage System	China	3 MW/17.2 kWh	Voltage sag mitigation
	Spain	4 MW/5.6 kWh	Frequency stability
Flywheel energy storage	USA	20 MW	Frequency regulation and power quality
	Japan	235 MVA	High power supply to nuclear fusion furnace
Superconducting magnetic energy storage	Japan	10 MW	System stability, power quality

more bulk or area, which limits their widespread use. For example, lead–acid (LA) batteries have features that include an easy way to charge, an easy way to recycle, and a favourable cost/performance ratio, with a cycle efficiency of 80–90 % and a service life of 1500 cycles at a depth of discharge, the typical service life is 6–15 years (Hesse et al., 2017). These features make it the most common type of battery used worldwide. However, its lower energy density and use of lead are the main limiting factors.

B. *Cost:* several ES technologies can be costly for manufacturing, setup, and maintenance. In some applications, the expense of materials and components combined with the requirement for modern technology might make ESSs less economically feasible. According to recent studies, there is a greater potential use for lithium-ion (Li-ion)-based batteries in utility grid integration, where it is employed to reduce fluctuations in RESs (Liu et al., 2021). Its cost in early 2000, was over $1000/kWh; by 2021 that cost has reduced to about $200/kWh (Amir et al., 2023). However, the cost of Li-ion batteries has to come down more to incorporate RESs completely in grids or even to mitigate demand peaks and valleys (Huang et al., 2018).

C. *Limited life expectancy:* Because of internal cell component deterioration, ES devices have a limited lifespan that varies depending on their operating circumstances (Lubello et al., 2021). This deterioration increases the replacement and maintenance costs (Aaslid et al., 2022).

Moreover, the disposal of certain ES devices after reaching the end of their useful life can pose environmental challenges. In contemporary research, the prevailing focus is directed towards energy management strategies encompassing battery degradation analysis within the context of stochastic micro grid operations, with the overarching goal of extending the anticipated service life of ES systems (Abdulla et al., 2016). The approach employs stochastic dynamic programming within a model Predictive control framework to iteratively select optimal charging or discharging strategies, aiming to maximize the long-term value of the energy storage asset. Incorporating forecasts of generation and demand as part of the solution is demonstrated to enhance the overall value achieved (Shaqsi et al., 2020). Furthermore, the ES systems are not capable of releasing the entire stored energy for later use, implying inevitable wastage during the storage and release process. The reported values for this wastage vary between 10 % and 30 % across different systems, with specific conditions attached to each area contributing to these variations (Walawalkar et al., 2010). Table 5 indicates that, in terms of efficiency, superconducting magnetic energy storage (SMES) and supercapacitors (SCs) stand out as the most advanced technologies.

Table 7 gives the advantages, limitations, opportunities and threats of different energy storage technologies (Statista, 2023), (Walawalkar et al., 2010).

Table 7
Strengths, Weaknesses, Opportunities, and Threats of different energy storage technologies.

ES Types	Strengths	Weaknesses	Opportunity	Threat
PHES	Higher capacity Elimination of power electronic converters Fast time response Higher life expectancy. Dispatchable Cost-effective per kilowatt	Location Limitations Ecological obstacles greater initial investment cost	Can be applied to offshore wind farms, utilizing a submerged lower reservoir beneath the ocean surface.	Increasing public resistance is due to the environmental damage caused. With the adoption of distributed storage, this feature might cease.
BES	Distributed and Dispatchable Faster time response Higher energy density and efficiency	greater initial investment cost shorter life expectancy In colder environments, might pose challenges or issues.	Due to advancing technology, the BES is expected to evolve into a distributed system including customer's participation.	Environmental concerns Constraints related to raw materials. Safety hazards due to potential overheating, chemical leaks, and fires.
CAES	Higher capacity Elimination of PE converters Cost-effective per kilowatt Storing energy for a duration spanning more than a year Storage losses are negligible	needs an underground storage facility If turbines are employed, gas becomes a necessary component in the process	Beneficial for distributed storage applications	Fluctuating fuel prices The prevalence within thermal power plant applications
HES	Eco-friendly Distributed storage	Lower Efficiency Dependent on consistent loading conditions Greater initial investment cost	Dedicated converters offer advantages over battery electric vehicles	Difficulties related to power electronic systems.

PHES pumped hydro energy storage, **BES** Battery energy storage, **CAES** compressed air energy storage, **HES** hydrogen energy storage

7.2. Role of Demand Response (DR) for Power System Stability in Smart Grid

7.2.1. DR objectives

DR entails managing loads in the short term to steer energy consumption by market regulations. DR may be specifically defined as the shift in the user's energy portfolio beyond their typical usage. According to Eid et al. (2016), load is directly impacted and controlled by the perks and privileges of DR schemes. This is a major benefit of DR, and it is the reason why DR programs are increasingly being used to create new market regulations and replace older demand-side management (DSM) methods.

Fig. 15 shows how DR may be utilized in many different configurations to alter the typical power consumption. Peak-clipping DR attempts at minimizing power usage during peak times. Load shifting DR is targeted at reducing power use during peak hours and moving it to off peak times. Comfort for flexible load customers may also be achieved via the use of strategic load increase and dynamic flexible load DR (Muratori et al., 2014).

The increased efficiency of the power system results from DR being compatible with real-time operations. Time is segmented into short, medium, and long intervals to facilitate this achievement. As a bonus, DR helps to maintain the electrical flow within the practical limits of the system in the short and medium term. The network's peak is reduced, preventing a collapse in the system. DR reduces generation in the long run. System efficiency is improved, and the cost to maintain the network is reduced. DR provides a logistical partnership between an electronic system and fluctuating market prices. Optimizing (dayahead, hour-head, DG, and RESs), minimizing (peak) loads, balancing (demand and supply), and maintaining real-time control are all key components of DR's time-based pricing model. In addition, there is a decrease in network costs and carbon dioxide (CO2) emissions by the practical implementation of DR programs.

7.2.2. DR in power systems

There are several techniques to trigger DR in the electric power system. This is discussed in detail in (Newsham and Bowker, 2010) in the form of interruptible and cost-based DR plans. Interruptible DR Program: These initiatives are contractual to ensure consistent supply.

They may be broken down further into load shedding, brownouts, and direct load control (DLC). The DLC functions via the idea of a hub, which may be anything from an aggregator to a system operator. Overload authority and the ability to adjust system settings as needed are both within this factor's control. Load shedding is a strategy for easing the pressure on the power grid caused by a shortage of resources (Qdr, 2006).

Price-Based DR Program: According to David and Lee (1989), this technique involves a deviation from the customer's usual pattern of power use due to the time-varying nature of electricity prices. The theoretical consequences of price-based DR on large-scale enterprises were discussed in Borenstein (2005) demonstrates the numerous sorts of accessible pricing techniques. Planned pricing structures include real-time pricing (RTP), critical peak pricing (CPP), time-of-use, and peak time rebates (PTR). This DR program has the potential to drastically reduce consumption in the event of an interruption. The system operator is responsible for achieving this. Furthermore, ToU in conjunction with demand shift leads to peak load balancing (Aghaei et al., 2016).

7.2.3. DR integration with power system

In Fig. 14, we can see how DR is integrated into the electrical grid.

A. *Power System Operation:*

Voltage Stability: The concept of "voltage stability" (Grainger and Stevenson, 1994) refers to a power system's capacity to keep the voltage throughout all buses inside a specified range both when operating normally and after disruptions. DR's established abilities to minimize voltage violations by reducing transmission congestions make it a simple matter to attain this voltage stability (Kumar and Sekhar, 2012) Fig. 15.

Transmission Congestion: By objectively reducing the peak demand time, DR works to smooth out the demand profile. In this approach, DR reduces transmission congestion by lowering the necessary transmission capacity (Hayes et al., 2014). In addition, power flow analysis is essential for the efficient management of demand-side resources since it provides the quantitative values needed to assess the value of the power system's advantages (Kandasamy et al., 2017).

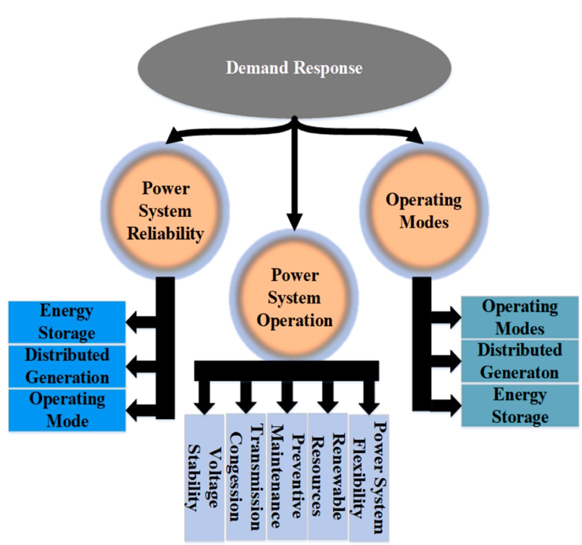

Fig. 14. DR Integration with Power System.

Preventive Maintenance: The DR's microgrids (MG) services are available regularly. Preventive maintenance is another name for this regularly planned servicing. When a component is nearing the end of its useful life or when a breakdown is anticipated, preventative maintenance may include its replacement or upkeep (Moura and De Almeida, 2010). DR's security-constrained preventive maintenance helps achieve fewer emissions, and lower fuel and reserve costs by determining the optimal power outage schedule.

Renewable Energy Sources: Research on RESs in the literature emphasizes their random nature. RESs are random, fleeting, and difficult to regulate. Numerous scholars have attempted to quantify the erratic behaviour of RESs at the different levels of DSM. Priority-based DR, however, may be used to get around the intermittent nature of an energy storage system based only on solar photovoltaic (Gitelman et al., 2017). Nonetheless, in the event of low production across RESs, DR may shorten the duration of peak energy use. In addition, it may prove to be a valuable method for keeping modern nuclear power reactors adaptable (Rosso et al., 2011). The optimization approach used to handle generation from rapidly ramping generators in SG via DR is studied in (Jabir et al., 2018).

B. *Power System Reliability:*

Design, planning, and operation are all crucial to ensuring a reliable power system. The dependability of the electrical grid depends on its efficiency and safety. The first one prioritizes meeting client needs by putting in place the necessary hardware. The latter, however, classes its actions in response to the unexpected power system disruption. In addition, classification of the system according to generation, transmission, and distribution is necessary for reliability evaluations of the power system. As a result, we conduct our studies across three distinct levels of organization, i.e. there are three hierarchical levels (HLs) in the examination of power system reliability. First-order analysis HL1 involves generating facility. Both power plants and transmission networks may be analyzed by the HL2. HL3 examines the logistics centre. Research into HL1 and HL2 is standard practice. The nature of widespread distribution problems,

however, means that HL3 assessment is challenging. The purpose of HL1 and HL2 is to improve load point reliability via DR. Moreover, HL3 via DR narrows down the disturbances on the client side. Therefore, HL3 is studied separately from HL2 and HL1 (Leithon et al., 2017).

C. *Micro Grids Operating Modes*:

When explaining the various MG modes of operation, the literature considers the fact that MGs are often linked. Nevertheless, many researchers favour the standalone operating mode since it may serve as a replacement for providing remote locations or places without conventional grids. Therefore, there are options for both connected and disconnected modes of operation. Decentralization of power plants is made possible by distributed generation (DG). The involvement of RESs makes this option a reality. Users may now take part in the electric energy system on both a personal and a societal level. Reduced power prices are a policy-driven a side effect of DR's ability to capture and enhance RES electricity generation. DR is an effective strategy for reducing the randomness of RESs (You and Segerberg, 2014). However, an imbalance issue has emerged at various network nodes (Chua et al., 2011) due to the growing prevalence of DGs based on RESs and additional loads in the form of EVs. The current in a neutral line may be adjusted to restore equilibrium in this situation. This neutral line flow has to be at zero if the distribution network (DN) is to be considered balanced. Neutral line current flow should be employed as a warning signal, as proposed in Chua et al. (2011). This alert allows the ESS operation to be adjusted to maintain the necessary voltage balance. In addition, uncertainty DR is paired with on-load tap changers (OLTCs) transformers with dynamic load controllers to manage voltage unbalancing difficulties brought on by RESs. To cause as little discomfort as

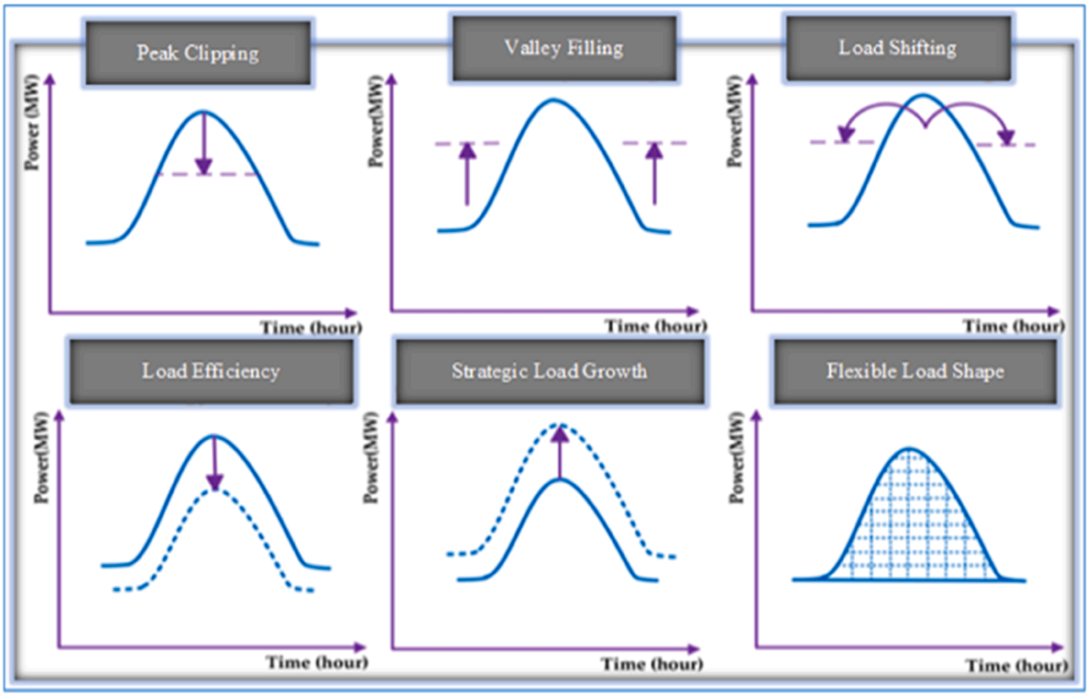

Fig. 15. Response strategies.

possible to the chosen users, DR helps to make that selection (Rahman et al., 2018). Capacitor banks are necessary because fluctuations in demand cause voltage unbalancing issues, which manifest as power imbalances in the commutation processes of inductive loads as a whole (Montoya et al., 2013). According to the research cited in Han et al. (2012), DG components may dampen power outages. To fulfil this fluctuating need, current MGs use PVs and WFs with the aid of Maximum Power Point Tracking (MPPT) controllers (Ou and Hong, 2014). In addition, the MG has cut the reaction time to voltage or power unbalance to 0.1 s. The literature demonstrates the increasing popularity of energy storage methods that use electric batteries or electric accumulators (Luo et al., 2016). Additional information on thermal storage may be found in Giuntoli and Poli (2013). The purpose of water storage in Gao et al. (2014), Kumar et al. (2023) is to provide backup power. The storage system's primary goal is to smooth out the peak-use consumption curve.

Microgrids are local energy grids that can operate independently or in conjunction with the traditional centralized grid. Microgrids can offer enhanced resilience, flexibility, and reliability. By integrating different Distributed Energy Resources (DERs) including solar panels, wind turbines, and BESS, these microgrids are able to operate during grid outages and extreme weather scenarios. Microgrids deliver several important benefits, such as the capability to island during grid outages to supply power to critical infrastructure; improved flexibility and reduction of peak load stress; enhanced efficiency through location close to load centres and energy storage; and assistance for renewable energy integration and grid stabilization (Waseem et al., 2020b).Microgrids are especially beneficial in regions that are subject to natural disasters or are equipped with an unreliable grid connection. There are several approaches that can be taken to improve microgrid deployment whilst also enhancing greater networks (Khan et al., 2024a). This could involve the adoption of smart inverters, automated demand response, and real-time monitoring devices; the use of AI and ML to optimize performance; the creation of hybrid microgrids with diverse sources of energy; the establishment of microgrid energy trading networks; the design of systems for bi-directional flow of energy to the larger grid; the definition of communications protocols to allow interoperability; and a focus on deployment to critical infrastructure and high-risk areas (Waseem et al., 2021). Some early examples of successful microgrids around the world For example, Puerto Rico has implemented solar-powered microgrids to improve energy resilience following Hurricane Maria, while California has applied microgrids as part of its wildfire mitigation response (Aziz et al., 2021).

7.3. Demand response scenarios in research practice

The management skills of an MG may also be improved with the help of several different mathematical solutions. To evaluate linear equations in MG, the authors of (Khan et al., 2016) made use of the general algebraic modelling system (GAMS) package. It is used to address problems of a generative nature. A mixed-integer linear programming (MILP) model with several scenarios was constructed for energy management in Alharbi and Raahemifar (2015). MG's scheduling issue is a mixed-integer programming (MIP) problem, and a complicated solver is employed to solve it (Talari et al., 2015). Large-scale MILP problems are no match for the sophisticated solution, as shown in Falsafi et al. (2014). Another method that relies on GAMS is the sparse nonlinear optimizer (SNOPT). This program is useful for resolving nonlinear optimization issues. The SNOPT solver (Gurobi Optimization, 2023) is used to find a solution to the non-linear programming issue posed by the modelled energy management system. The Gurobi optimizer is used to optimize MILP issues (Elçi and Noyan, 2018) also employed this optimizer for computational purposes.

The Probability Density Function (PDF) of random variables may be estimated with the help of stochastic techniques (Dantzig, 2004). Dantzig was the first to model uncertainty using stochastic processes (Xie et al., 2018). However, the input elements must be known to employ such a technique (Wang et al., 2018). Models with uncertainty may utilize the PDF to generate scenarios. As part of the procedure, PDFs must be split up into individual pieces. Each section is then broken down into possible outcomes. Individual component probabilities are clustered in the desired probability region (Rabiee et al., 2016). To deal with the unknowns associated with PV and WT (Ahmed et al., 2019), the authors of Shields (2018) used scenario-based generation. The scenarios in Dufo-López et al. (2016) were represented by discrete distribution sets to account for the unknowns of solar, wind, and load-generating systems. Random scenarios for sun, wind, and loads are generated using Monte Carlo Simulation (MCS) and a roulettewheel mechanism. The scenario reduction method is also designed with efficiency in mind. Modelling PV and WT using MCS is described in Caralis et al. (2014). In Peik-Herfeh et al. (2013), histograms and other indicators of stochastic criteria are utilized to analyze the data obtained. The MCS technique is used to analyze investments in wind energy production to control uncertainties, as shown in Suganthi et al. (2015). The optimization approach is used in Assad et al. (2022) to analyze solar power hybrid system uncertainties (Soroudi and Ehsan, 2011). uses the point estimation method (PEM) to simulate the unpredictability of renewable energy sources like the sun and wind. In Zhang et al. (2016), the uncertainty between market pricing and generating resources is modelled using a probabilistic price-based unit commitment. Fuzzy theory's uses in RESs were discussed in detail in Kuznetsova et al. (2015). Parametric uncertainty is addressed in Casisi et al. (2015) using a robust optimization approach with unknown limits. Robust optimization is of particular use when PDF parameters are unavailable. To deal with load uncertainties, Chen et al. (2017) employs this technique. Additionally, rigorous optimization was used to improve solar and wind power generation in de Cerio Mendaza et al. (2014). Assumptions form the basis of the Information gap decision theory (IGDT), a method of decision-making. In addition, Haider et al. (2016a) uses it to determine optimal bidding for day-ahead market pricing. The IGDT-based method for comparing the purchasing practices of major clients was adopted in Haider et al. (2016b). Greater control may be obtained in the case of increasing energy demand thanks to the DR feature of MG, which allows for greater coordination between demand and supply. Achieving the best DR plan, however, is a multitarget optimization challenge. Numerous optimization methods have been proposed in the literature as potential answers to these issues. Swarm-based algorithms, quasi-static methods and mixed-integer strategies are all examples. These strategies aim to reduce energy usage by optimizing technical characteristics, imposing constraints on operations, and balancing energy use throughout a system.

Mutual operation of available DGs is achieved in MGs to improve load management. System stability and maximum economic advantages may be achieved with the use of mathematical processes via the combination of optimization and DR. Having automation available further enhances DR's capacity to prevent frequent disconnections. The real-time pricing systems were automated in Chen et al. (2017) to compensate for voltage fluctuations at EV charging stations. Protocols for optimizing networks have been developed to improve DR actor communication and meet fluctuating demand. Ref de Cerio Mendaza et al. (2014) suggested combining DR with hierarchical power network topologies to further improve its control capabilities. These setups satisfied consumers' comfort requirements via network-wide dynamic operation eliminated the need for redundant circuits and accommodated variable load sizes. Because of this, distribution was enhanced, and the system's minimum voltage was maintained.

Automatic load control solutions often demand consumers to preserve the agreement of reduced bills by permitting only assigned consumption sanctioned by DR, as was shown by Haider et al. (2016b). However, when consumers take part in DR programs, they may see adverse shifts in retail pricing and demand. Because of this multiplicative disturbance, dynamic demand management algorithms proved to be the most effective solution. These algorithms' major focus is on minimizing both energy use and real-time cost. To put the user in command of their energy usage, these algorithms also incorporate automated control systems.

Virtual Power Plant (VPP) is a novel control architecture for managing electrical power. Conventional technologies and Distributed Energy Resources (DERs) may be managed with the use of network communication. According to Mocci et al. (2015), communication between users and the network is two-way. In assessing the efficacy of widespread DR implementation, this two-way connection is crucial. Smart networks may also increase the longevity of a system. Dynamic load profile analysis may help with this. When DR is concerned with minimizing power losses inside DN, inter-node communication takes centre stage. As a result, DR may benefit greatly from a framework that facilitates optimum network reconfiguration to determine the optimal network configuration. Redesigning transmission and domain names DN are both part of the SG idea. Besides delivering advantages like lower losses and better grid operations, it also supports the market for DGs. In addition, DR in SGs may help reduce energy use during peak hours without sacrificing customers' convenience (Helmi et al., 2021). As electrical networks evolve, MGs are more relied upon to take control of DR management. All of the network's users may be coordinated by MG.

In addition, ESSs, RESs, and non-RESs are used in the development of current MGs. This aids DR demand management efforts. MGs may trade in both directions because of their updated structure. Within an MG, this management system handles the procurement and sale of energy. Asymmetrical failures like short circuits, grounding, and open conductors are also a problem for MG. Ou (2013) outlined asymmetric failure analysis methodologies and built two matrices to help deal with these complications. Current injection into the buses is described by one matrix, while voltage imbalance and bifurcated currents are described by another. As a result, MG will be able to produce technically sound work. It should be noted, however, that incentive-based DR programs may aid with MG control by cutting down on use during peak hours. Consequently, DR is maximized concerning the cost of the provided energy.

8. Controlling mechanisms

To handle the previous challenges (e.g. FRT and decreasing level of inertia) presented by the dynamic nature of RESs and EVs which changing the landscape of the power system framework, this section examines the approaches and control mechanisms put in place to ensure grid stability. The fault ride-through abilities and strategies of integrated RESs through the power electronic converters are essential for power grid stability as they influence both active and reactive power. Therefore, to accelerate the energy transition of the future grid, the focus should be directed and increased towards enhancing FRT schemes (Meegahapola et al., 2020). Diverse control strategies have been adapted to achieve VRT and reactive power assistance for various RESs. These strategies can be external devices or enhanced controllers to absorb/inject reactive power to maintain the voltage at a specific limit. As the DFIG is commonly utilised, and the classification of LVRT techniques is also included in Fig. 16 (Mahela et al., 2019).The authors of (Király et al., 2023) offered an extensive examination of managing Static Synchronous Compensators (STATCOMs) to enhance the stability of power networks when incorporating RESs and EVs. The paper tackles pivotal stability issues linked to rotor angle, voltage, and resonance in power systems connected with wind turbines, PV, and, or EVs. Furthermore, it delves into the hurdles and approaches associated with power system stability involving PV, EV, and wind turbines. Additionally, it discusses STATCOM control, vital for upholding voltage stability in power systems. It explored the role of frequency control in balancing generated and consumed power within a power system experiencing significant renewable energy integration. It specifically incorporates the automatic generation control secondary frequency control to facilitate robust cascading failure modelling and analysis. The authors have built a model that integrates the dynamic aspects of frequency control to simulate cascading failures within contemporary power systems. Additionally, it elucidates the functioning of automatic generation control, which generates power change signals to fine-tune generator output in response to area control error (ACE). The authors of (Gao et al., 2014) introduced a control structure termed V2G, designed to integrate EVs seamlessly within the contemporary power grid. This framework integrates novel electric elements such as renewable energy sources, micro-grid infrastructure, and adaptable electric devices. Leveraging the onboard batteries and adaptable power regulation of EVs, they function

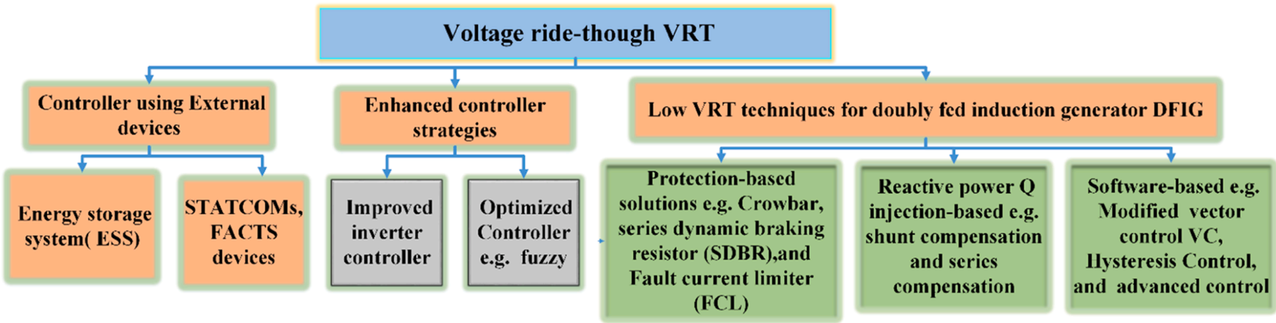

Fig. 16. Voltage ride-though Classification.

as decentralized energy storage units. A dedicated EV aggregator consolidates power from numerous EVs and engages with the grid operator via a bidirectional communication network. Moreover, this aggregator oversees the allocation of V2G power to individual EVs and keeps track of the status of EV batteries to locally compensate for fluctuation of renewable energy sources such as wind turbines with fast response. Also, they developed a hardware-in-the-loop (HIL) system to execute software simulations, control power converters, and confirm the accuracy of the simulation model through measured outcomes.

The research works on reactive power control in grid-integrated RESs are thoroughly analyzed by the authors of (Kumar et al., 2023). In addition to analyzing a variety of research papers gathered between 2010 and 2022, the study discusses control strategies, support devices, controllers, and optimization algorithms. It also assesses the benefits and drawbacks of the reviewed literature for reactive power flow management for HRES. A variety of modern and conventional reactive power regulation systems utilized in power grids with high integration of RESs are covered in the literature review. The traditional reactive power controlling mechanisms are like On-Load Tap Changers transformers (Hu et al., 2022b), and Doubly Fed Induction Generators (Ikeda et al., 2021). The modern controlling mechanisms such as inverter-based (Burbano-Benavides et al., 2021), and energy storage system (Caruso et al., 2015).

8.1. Case study

In 1882, the world's first transmission line utilised direct current (DC). Approximately eight years later, the "War of Currents" took place between Nikola Tesla, who proposed alternating current (AC), and Thomas Edison, who supported direct current (DC). Tesla emerged successful in this war, resulting in the widespread use of AC. However, DC continues to be used. By the mid-twentieth century, over 200 DC-powered projects had been created around the world, demonstrating efficient and dependable transmission, particularly over long distances and in bulk power. Fig. 17 shows increasing in HVDC Capacity over the years. This increasing trend can be attributed to the diminishing cost-effectiveness of HVAC systems over extended distances, due to the escalating losses and the compensated requirements for control equipment necessary to ensure system stability. Table 8 summarized comparison between HVAC and HVDC (Alassi et al., 2019).

Furthermore, because HRES offers many voltage systems and levels, notably DC from photovoltaic cells and AC from wind turbines as shown in Fig. 18. Adopting DC voltage will boost system diversity and may be considered an effective solution to interconnect systems with large-scale

Table 8
HVAC versus. HVDC.

Comparison	HVAC	HVDC
No. of conductors	Higher (3 phases)	Fewer (Bipolar)
Utilization	Limited because skin-effect	Fully in the thermal limits
Losses	More (resistively, and reactive losses, thus expensive line compensators required)	Less (mainly resistive there are no reactive losses)
Protective Devices	Well-Developed Ultra High Voltage C. Bs	limited with significant predicted growth
Cost at a shorter distance	Significantly Lower	Higher (converter stations)
Equipment of synchronism	Required	supports asynchronous interconnection
Loading& Insulation	Insulation requirement higher than HVDC by $\sqrt{2}$	loaded to $\sqrt{2}$ times higher than rated HVAC.

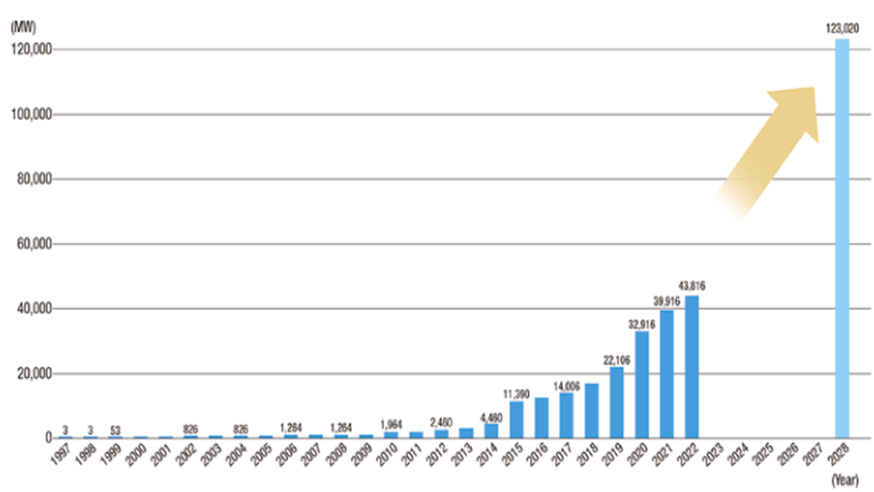

Fig. 17. The trend of using HVDC (Ou, 2013).

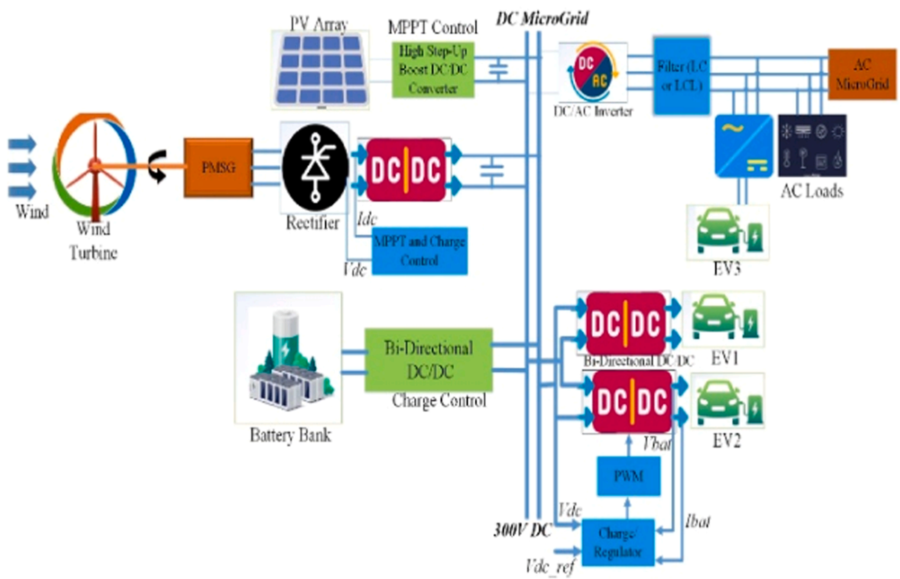

Fig. 18. DC and AC Microgrid.

integration of RES and different locations to mitigate the variability of the system. To demonstrate this, the CIGRE Working Group B4.57 (B4, 2019) has been taken as the case study, with the integration of RESs to the model and the lumped load to the system as shown in Fig. 19. First, the two transformers are connected using a high-voltage transmission line AC, and the 3-phase fault is initiated at 1 sec. and simulated using DIgSILENT as network disturbance at TACSysINV2 (AC bus). This fault is assumed to be cleared at 1.2 s by the protection system. The voltage bus in p.u. during all these events is shown in Fig. 20. In the second scenario, the HVDC connection link is used, and the system is simulated with the same set of parameters by controlling the rectifier and inverter systems, the simulation result is shown in the same figure. By performing a comparative examination of the two systems, it is evident that the application of HVDC technology demonstrates a higher degree of stability, as demonstrated by the finding that the bus voltage does not reach the magnitude noted in HVAC systems. Furthermore, Power electronic converters with cutting-edge technology allow load current to be controlled with fast response, thereby effectively regulating the injection of active and reactive power, as shown in Fig. 21 and mitigating the system's stability. Unlike standard grid-following converters, Grid-forming converters (GFM) are advanced power electronic devices that help to maintain and support the electrical grid, especially at RES integration where the standard grid-following converters synchronize their output power with the existing grid's voltage and frequency, GFM within HVDC can establish and manage their frequency and voltage effectively to manage RES fluctuations. In the future, the rating of these converters is anticipated to be enhanced to handle the substantial power generation capacity of Renewable Energy Storage Systems plants.

9. Challenges and future recommendations

As previously discussed, the intermittency of renewable energy sources and electric vehicles poses significant challenges to achieving 100 % integration of RES. Achieving 100 % RES introduces significant operational complexities, particularly in maintaining voltage regulation and frequency control. Unlike conventional generators, RESs lack

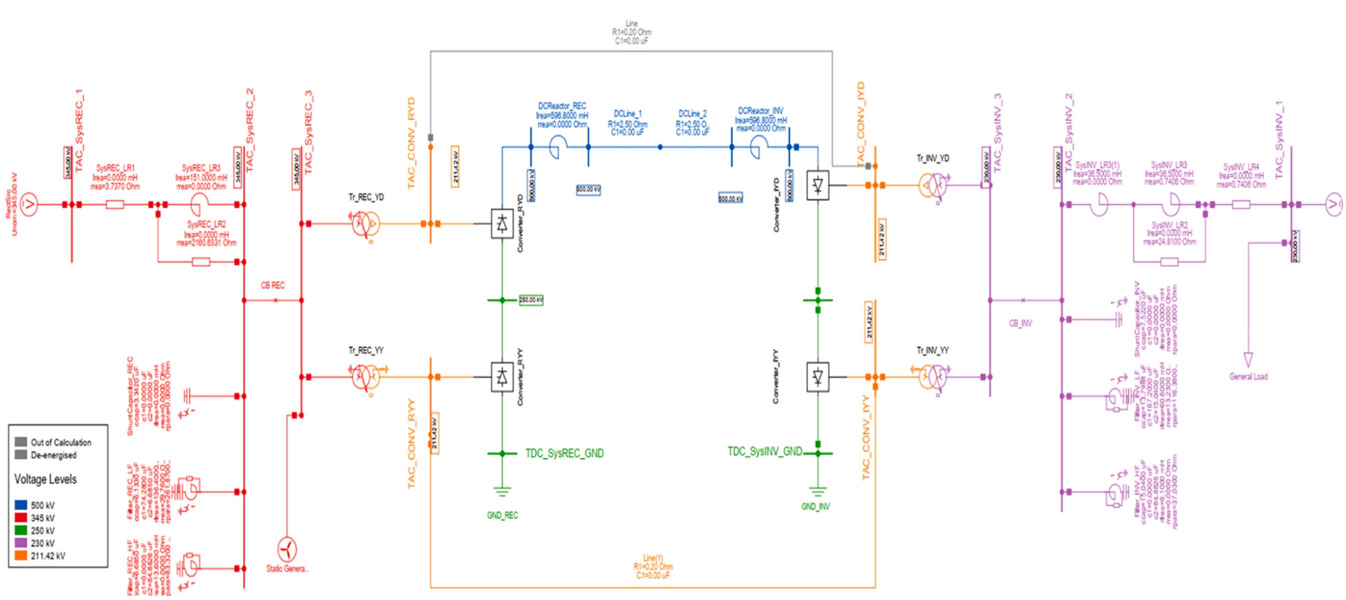

Fig. 19. Electrical network (Assad et al., 2022).

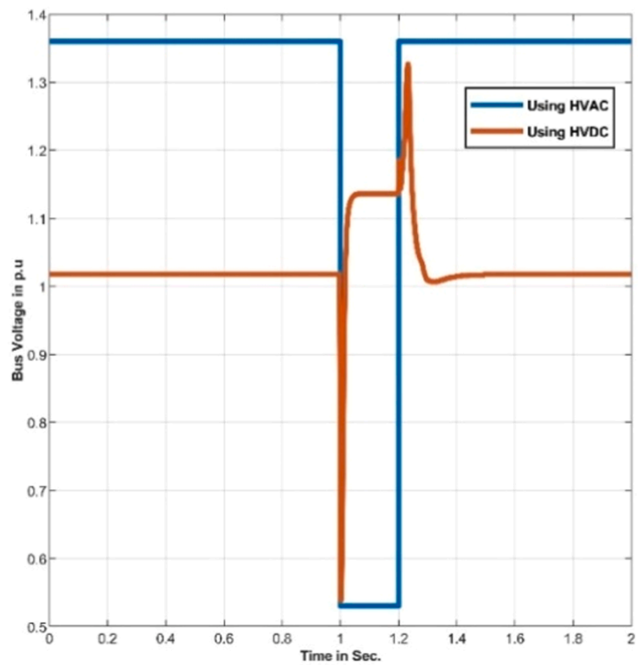

Fig. 20. Bus voltage using HVDC and HVAC.

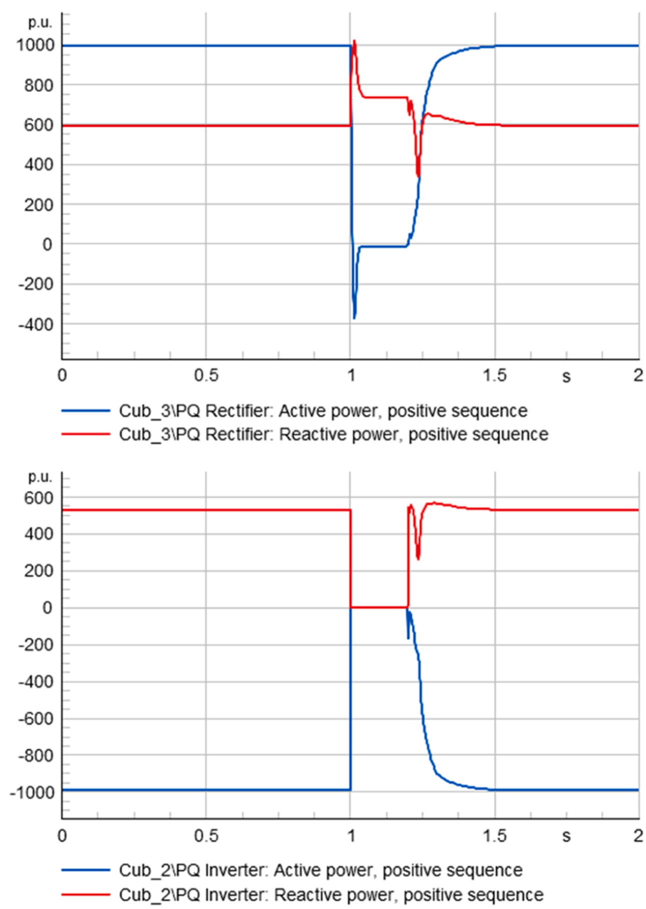

Fig. 21. Active and reactive power of the power electronic devices.

inherent inertia and contribute minimal reactive power. Large-scale integration can help mitigate these challenges, with HVDC interconnections emerging as a key solution. HVDC technology is particularly effective for long-distance bulk power transmission and the large-scale integration of RESs, offering advantages such as minimal losses, enhanced network stability, reliability, cost-effectiveness (especially for

extended distances), and asynchronous interconnection capabilities, as outlined in Table 8.China has suggested an ambitious plan to construct a worldwide energy connection network using Ultra-High Voltage Direct Current (UHVDC) transmission technology. This plan seeks to promote the seamless integration and transmission of RESs across continents, resulting in a more efficient, dependable, and sustainable global energy system. This project not only promotes the large-scale deployment of renewable energy sources such as wind and solar, but it also encourages international collaboration in tackling global energy concerns such as decarbonization, energy security, and fair energy distribution (Saleh et al., 2024), (Lei et al., 2022). However, implementing HVDC systems also presents notable challenges. These include high initial costs, environmental concerns (particularly with submarine cables, such as disturbances during cable placement, heat emissions, contamination, and underwater noise), DC voltage control issues, technical challenges (including grid codes and standards), harmonics, DC circuit breaker design, and protection challenges. The latter arises due to the high short-circuit current and the absence of zero crossing in DC systems. To enhance the performance of HVDC protection systems in the future, greater emphasis should be placed on advancing protection techniques (Farkhani et al., 2024).

Furthermore, to mitigate the uncertainty of RES, utility-scale energy storage systems must be diversified. lithium-ion (Li-ion) batteries, flow batteries, and power-to-gas (P2G) systems are the most promising and key elements and have different benefits and disadvantages. As pumped hydropower energy storage has geographic restrictions, these three technologies require increased focus from both research and industry to facilitate their development and deployment as utility-scale energy systems. As shown in Table 5 Lithium-ion batteries offer excellent energy efficiency, extended cycle life, and high energy density and can be used as grid-scale energy storage to enhance power system stability by offering services such as frequency regulation, peak shifting, renewable energy integration, and power management. Flow batteries, particularly redox flow batteries, are characterised by long lifespan, high cycle life, safety, and have distinct benefits for energy storage, particularly in applications that need medium- to long-term storage. Their design enables independent scaling of power and energy (defined by the size of the electrochemical stack and the volume of the electrolyte tanks), making them ideal for grid stability and backup power (Yin et al., 2024). However, these types of batteries may exhibit lower energy and power density compared to Li-ion and potentially higher upfront costs as shown in Table 5. Therefore, extensive research is needed in this direction to make them more competitive compared to Li-ion batteries. The P2G concept is related to the P2X concept. In the literature, various definitions of the Power-to-X (P2X) concept have been proposed, reflecting its diverse applications and interpretations. For instance, in Denmark, DANSK ENERGI defines P2X as the conversion of green power into hydrogen or other PtX products. This emphasizes its role in utilizing renewable energy to produce versatile forms of energy carriers or materials. Similarly, another perspective, as outlined in scholarly works, defines Power-to-X technology as a system that converts electrical power (P) into other forms of energy or products (X), such as gas, liquid fuels, chemicals, or heat. This conversion process leverages renewable energy sources, enabling the generation of sustainable and adaptable energy forms that can support various industrial, transportation, and energy storage applications. These definitions collectively highlight P2X's potential as a transformative technology in advancing the energy transition towards sustainability and decarbonization (Sorrenti et al., 2022). The grid-forming inverter is the critical interface between energy storage technology and the grid, however, there are no industry standards for developing new grid-forming control with BES generation that aligns with evolving power system paradigms. To overcome this lackness many research proposals might be made. First and foremost, control algorithms for grid-forming inverters must be developed and standardized to ensure widespread adoption and compatibility with current grid infrastructures. Establishing performance benchmarks for these inverters under various circumstances, including changing grid states and load changes, and integrating cutting-edge technologies would aid in improving efficiency, dependability and power system stability. However, the grid's integrity is in danger due to cyber attacks, making cybersecurity a key problem with this development, therefore, implementing strong measures like Network Intrusion Prevention Systems and Network Intrusion Detection Systems is essential for strengthening defences against attacks (Khan et al., 2024b). Furthermore, advanced simulation and modeling methods should be used to forecast the behavior of grid-forming inverters, allowing for the design of resilient and efficient systems. Extensive field testing and pilot projects are required to collect real-world data that can be used to improve control techniques and system design. Interdisciplinary collaboration among academia, business, and regulatory organizations is critical for addressing technological and regulatory difficulties, resulting in complete standards and best practices.

In addition, before implementing these systems, it is very important to have a robust cyber security implementation so that these systems are not hacked and the power grids remain stable and flexible. Such analysis is potentially necessary to guide economic evaluations in the cost-benefit analysis of grid-forming inverter installation versus the long-term merits (costs) of increased stability in the grid. Lastly, advocating for government and regulatory policies that will incentivize grid-forming inverter use, like R&D tax credits, will enhance deployment and operations efficiencies. Focusing on these areas fills some of the gaps between what we can do today and what modern power systems will require.

Because inertia will decrease with more power systems where the generation devices are connected only with the inverter, synchronous condensers installation is necessary to stabilize the system. Moreover, AI and ML techniques can be applied to evaluate real-time stability, predict key events, and create adaptive control methods (Saleh et al., 2024).

10. Conclusion

Throughout this work, we have explored the complex link between energy transition to RESs and power system stability. The energy transition from traditional fossil fuels to renewable energy sources has presented opportunities and difficulties for the power system. The primary concern emerging from our investigation is the essential role that power system stability plays in enabling a smooth energy transition. However, the inherent uncertainty and low inertia of RESs introduce operational challenges and threaten power system stability. While various research papers have addressed RES integration and design, there is a scarcity of research articles focusing on stability in distributed generation networks with RESs.To guarantee reliability, resilience, and sustainable power distribution, this stability acts as the cornerstone, facilitating the smooth integration and communities need to work together. This paper aims to fill that gap by providing a comprehensive review of the benefits, challenges, and integration of RESs and electric vehicles (EVs), along with tools, software, controlling mechanisms, and potential solutions related to RES integration. Our case study on integrating HVDC technology with hybrid RES demonstrates that HVDC enhances long-distance power transmission efficiency, reduces losses, and improves grid stability, making it an effective solution for variable RES generation. The simulation results using DIgSILENT/MATLAB software show that the HVDC link is more stable than HVAC transmission in terms of voltage stability when integrating RESs, which could otherwise result in voltage limit violations. The presence of DC voltage makes the integration of RES more efficient and smoother. Thus, 100 % RES integration may proceed more smoothly and efficiently with the presence of DC voltage. In addition, to mitigate the power system instability due to the variable RESs integration, diverse energy sources and storage should be used. Furthermore, end-user consumers should of RESs in our systems. However, accomplishing this shift will require teamwork, legislators, business leaders, and researchers, to participate in the demand response strategy and their coordinated electric vehicles. We must move quickly to implement cutting-edge technology, controlling mechanisms, strong and incentive regulations, and well-informed plans to move our energy systems to resilience and sustainability in the different routine life requirements such as electricity and transportation.

CRediT authorship contribution statement

Saleh Ahmed Mohammed : Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Vokony Istvan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Waseem Muhammad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Khan Muhammad Adnan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Al-Areqi Ahmed:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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