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Review Article

A review of photovoltaic plants and battery energy storage systems in terms of power systems stability

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ABSTRACT

Nowadays, the rapid increase in PV plants in power systems has reached a point that may negatively impact power system stability. Battery storage systems have also begun to be integrated into power systems to mitigate the negative effects of non-rotating plants such as PV plants. The expected increase in PV penetration levels and BESS size must be analyzed jointly to address stability issues in power systems. It is evident that existing reviews on the hybrid integration of PV and BESS are limited. This paper aims to contribute to future developments by reviewing the most recent status and potential outcomes of studies related to the impact of PV plants and battery storage system (BESS) units on power system stability. The reviewed studies have been classified to provide valuable insights into the impact of PV plants and BESS units on power system stability. Each classification focuses on the studies in terms of the stability analysis type, the PV/BESS unit combination, the analysis method, the structure of the power system, the PV penetration level, the size of the BESS, whether frequency support is provided, and the use of simulation programs. In the classification of stability, frequency stability and rotor angle (for transients) stability are the most discussed topics. In the review for the units, it was found that studies on the stability of PV power plants were frequently addressed. In addition, studies on BESS and PV-BESS configurations have increased over time. Almost all stability studies focus on time-domain analysis. In addition, modal analysis, which is widely used in small-signal stability studies, is the second most frequently used analysis method in studies. In the studies, the effect of a three-phase short circuit fault on the stability of the system is usually analyzed. Apart from this fault, the implementation of a fault in the load is among the popular cases considered. In the power system classification used, either large or small power systems are usually considered. It is rare for an impact to be considered in both a small and a large power system. Different penetration levels and sizes of PV and BESS units, respectively, are usually analyzed separately in terms of stability. The number of papers investigating the effect of both PV and BESS together on the stability of a power system is quite rare. As a result of the classification on frequency support, it is seen that research on frequency support of PV power plants is handled from similar perspectives, although it has gained popularity recently. When the simulation programs used, which represent the last classification group, are examined, it is observed that DigSilent PowerFactory and MATLAB are generally preferred.

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INTRODUCTION

With technological developments and increasing carbon emissions, electrical power generation from renewable energy sources has gained considerable importance in recent years. In 2021, more than 306 GW of new renewable energy generation capacity was added to the total grid-installed power worldwide [1]. While photovoltaic (PV) units constitute 57.2% (175 GW) of this installed capacity, wind, hydropower and bio-power plants compose 32.7% (100 GW), 8.8% (27 GW) and 3.3% (10 GW), respectively [1]. PV units have been the most frequent renewable energy source in power systems since 2016 [1]. In 2018 and beyond, PV units have been incorporated into the grid at nearly twice the rate of any other renewable energy source [1].

The western parts of the Americas, the entire African continent, the Arabian Peninsula, Australia, and portions of Asia all demonstrate considerable solar energy capacity [2]. Table 1 lists the countries that show a high solar energy potential.

Table 1. The highest practical potential for countries

Country	Average (kWh/kWp)	GDP-2023 (USD)
Namibia	5.38	4742.8
Chile	5.36	17093.2
Jordan	5.32	4482.1
Arab Republic of Egypt	5.25	3512.6
Republic of Yemen	5.21	-
Oman	5.17	23295.3
Saudi Arabia	5.16	28895.0
Lesotho	5.13	878.0
Libya	5.12	7330.0
Botswana	5.11	7249.8

Considering Table 1, the gross domestic product (GDP) values of most countries with high solar energy potential are much lower than those of developed countries [2,3]. Therefore, it is safe to state that the economic development in these countries has also influenced the generation capacity of photovoltaic energy. In this regard, the data provided in Tables 2 and 3 point to the fact that the most developed countries possess the greatest installed capacity. Besides, Table 2 provides the total active power of all PV units installed up to the year 2021 [2,4].

Table 2 shows that nations with high GDPs are investing in solar systems, despite the lack of potential in many of them. It can be stated from the table that, although India and Brazil have lower GDPs, they have made more investments in solar energy compared to countries with higher GDPs.

Even in places with comparatively lower solar energy potential, there is a significant amount of PV installed capacity. This suggests that countries with greater solar energy potential, such as those listed in Table 1, will be able to add more solar energy to their grids. Furthermore, the positioning of PV power plants is paramount to achieving installed capacity goals in countries such as South Korea, Germany, China, Turkey, and Spain [1].

It is evident that the penetration levels of PV units are on the rise; however, this does come with some undesirable outcomes. A downside of PV units, as a renewable energy source with no rotating structure, is the reduction of the total moment of inertia within the power system [1, 5]. In addition, the sporadic generation due to the nature of renewable energy sources has another effect [5, 6]. This intermittent generation causes fluctuations in the electricity

Table 2. Countries with the highest total ınstalled capacity of PV units in 2021

Country	GW	%	Average (kWh/kWp)	GDP-2021 (USD)
China	308,5	32,75	3.88	12,556
USA	123	13,06	4.36	70,249
Japan	78,2	8,30	3.45	39,313
India	60,4	6,41	4.32	2,257
Germany	59,2	6,28	2.96	51,204
Australia	25,4	2,70	4.71	60,443
İtaly	22,6	2,40	3.99	35,657
Republic of Korea	21,5	2,28	3.82	34,998
Spain	18,5	1,96	4.41	30,103
Vietnam	17,4	1,85	3.55	3,756
Rest of the World	207,3	22,01	-	-
Sum of Top 10	734,7	77,99	-	-
Sum of The World	942	100,00	-	-

Table 3. The ınstalled capacity of PV units in 2021

Country	GW	%	Average (kWh/kWp)	GDP-2021 (USD)
China	54,9	31,37	3.88	12,556
USA	26,9	15,37	4.36	70,249
India	13	7,43	4.32	2,257
Japan	6,5	3,71	3.45	39,313
Brazil	5,5	3,14	4.40	7,507
Germany	5,3	3,03	2.96	51,204
Spain	4,9	2,80	4.41	30,103
Australia	4,6	2,63	4.71	60,443
Republic of Korea	4,2	2,40	3.82	34,998
France	3,3	1,89	3.39	43,659
Rest of the World	45,9	26,23	-	-
Sum of Top 10	129,1	73,77	-	-
Sum of The World	175	100,00	-	-

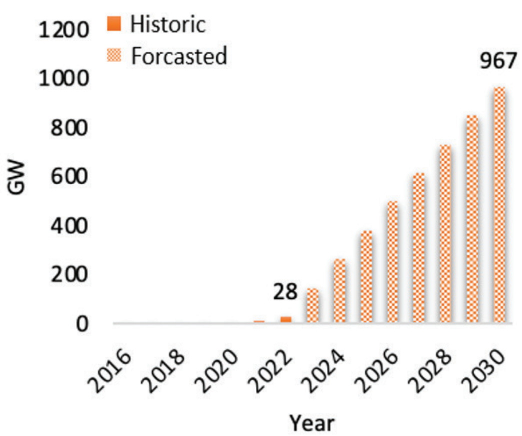
generation of PV power plants, either instantly or for a prolonged period on a cloudy day.

There has been an increase in the use of storage units to eliminate the negative effects of renewable energy sources. Energy Storage Systems (ESS) offer numerous advantages such as balancing energy supply, high efficiency, reducing energy costs, and reducing carbon emissions. Additionally, by providing services like frequency and voltage regulation, they greatly contribute to grid stability. The installed capacity of energy storage worldwide had reached 209.4 GW by the end of 2021 [7]. Most of these energy storage units are in the form of pumped hydropower. This form of storage accounts for the majority of energy storage systems worldwide, at 86.2% (180.5 GW), while new energy storage systems account for nearly 25.4 GW, of which Battery Energy Storage Systems (BESS) make up a substantial portion, approximately 95.7% (24.31 GW) [7].

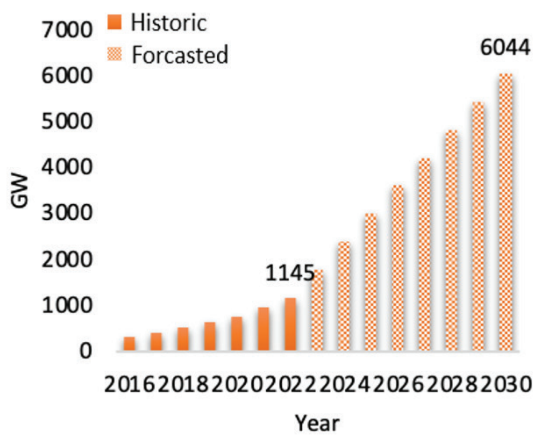
Motivation and Contributions

The shift towards renewable energy sources continues to increase globally due to various factors such as the depletion of fossil fuels, population growth, and the Net Zero Scenario. With increasing renewable energy generation, an increase in PV penetration levels and BESS sizes in power systems is expected, as shown in Figure 1 [8,9].

The expected increase in PV penetration levels and BESS sizes must be analyzed together to address stability issues in power systems. In the literature, there are review studies related to the integration of PV and BESS systems into the grid. Some of these are shown in Table 4. In [5], studies on technical solutions such as frequency regulation,



(a)



(b)

Figure 1. PV and BESS expectations fort he future.

low-frequency oscillation damping, voltage regulation, and fault-ride through for potential voltage, rotor angle, and frequency stability issues arising from the integration of large-scale PVs into the power system are discussed. The technical challenges of integrating PV systems into the grid in terms of voltage, frequency, protection, harmonics, rotor angle stability, and flexibility requirements are once again examined in [10,11] conducts a review on the integration of PV systems at high penetration levels into the grid, with a particular focus on regulatory considerations and stability issues. [12] comprehensively examines the problems encountered in the integration of PV systems into the grid and the proposed solutions. The study, which examines the problems in detail from technical, environmental, and socio-economic perspectives, also provides a detailed analysis of solutions in terms of grid codes, advanced control strategies, energy storage systems, and renewable energy policies. [13] includes a comprehensive review of applications on BESS sizing using different criteria and methods in renewable energy systems. In the study, sizing criteria are examined by categorizing them as financial indicators, technical indicators, and hybrid indicators. Similarly, the techniques used for sizing are examined under four distinct methods: probabilistic methods, analytical methods, directed search-based methods, and hybrid methods. [14] provides a comprehensive review of the current most suitable BESS sizing algorithms within the framework of optimization objectives and optimization constraints. [15] has helped to develop existing strategies by examining hybrid PV-BESS systems in six different areas: lifetime improvement, cost reduction analysis, optimal sizing, mitigation of power quality issues, optimal control of the power system, and peak load shifting and minimizing.

It is evident that existing reviews on the hybrid integration of PV and BESS are limited. This paper aims to contribute to future developments by reviewing the status and potential outcomes of studies related to the integration of PV and BESS within the framework of power system stability. In line with this purpose, the study's contribution to literature and the aspects that differentiate it from existing literature are outlined below.

- Studies in literature generally include different topics (economic, social, power system stability, device lifetime, grid codes, etc.) for PV or BESS. This prevents these studies from conducting a detailed analysis in terms of power system stability. In this study, both PV and BESS studies are analyzed in detail and from many aspects in terms of power system stability.
- This study provides the literature with an analysis of the effect of PV and BESS on stability separately, as well as

Table 4. Some of the review studies related to the ıntegration of PV and BESS

References-Year	Topic	Classification
[5]-2015	PV	-Impact on power system stability -Technical solutions
[13]-2018	BESS	-BESS sizing criteria -BESS sizing techniques
[11]-2019	PV	-Technical Challenges of Integrating High Penetration Levels of Small-Scale PV Systems into the Grid -Technical Challenges of Integrating Large-Scale PV Systems into the Grid
[10]-2020	PV	-Impacts of PV integration into power system -Limits of PV penetration -Modelling for grid stability & reliability assessment with PV
[12]-2022	PV	-PV systems grid integratıon challenges -Solutions for grid integratıon problems
[14]-2022	BESS	-Optimization objectives in BESS -Constraints on BESS optimization
[15]-2022	PV+BESS	-Lifetime improvement -Cost reduction analysis -Optimal sizing -Mitigation of power quality issues -Optimal control of power system -Peak load shifting and minimizing
This paper	PV+BESS	-Power system stability -Units -Analysis methods -Power system structure -Penetration level/size -Frequency support -Simulation programs

in studies where they are used together. It also shows that the studies on this subject are quite limited.
- This paper discusses the impact of the selected power system on stability analysis through studies in literature. In this respect, it provides a perspective for literature in the analysis of stability studies.
- This study presents a classification of the programs used for power system stability in literature. In addition, this classification result is compared with transmission and distribution operators.
- For each classification, studies with different features are discussed and compared in detail. The researchers' results are discussed comparatively, and a summary of the results obtained under the same classification heading is presented to the literature.
- The classification method in this study reveals which topics researchers in the literature focus on and which areas are less explored. In this respect, the study serves as a guide for researchers in the field by highlighting the missing points that can be researched in the literature.
- This study is a review of the most recent studies on PV and BESS in literature. As such, it provides an updated analysis of PV and BESS studies compared with previous reviews.

Power System Stability Analysis for PV Power Plant and BESS

Three distinct categories of power system stability can be examined: rotor angle stability, frequency stability, and voltage stability [16]. Separate divisions can also be made for stability, considering the duration and magnitude of the disturbance. Various factors are evaluated when examining these divisions. Figure 2 shows the classifications for power system stability.

The definitions for the power system stability classes shown in Figure 2 are given below [16].
- Rotor angle stability refers to the ability of interconnected synchronous machines in power systems to maintain synchronization. The stability of this synchronization depends on each machine's ability to maintain a balance between electromagnetic and mechanical torque. Rotor angle stability can be divided into two subgroups. Minor disturbances are considered in the first type of stability, which is small-signal stability. The second type, transient stability, deals with major disturbances.
- Frequency stability refers to a system's ability to maintain its frequency following a disturbance in the power network. This relies on the equilibrium between generation and consumption.
- Voltage stability refers to the ability to keep the voltage of all buses constant within prescribed upper and lower limits when a disturbance occurs in the power system.

Researchers have primarily focused on the control options, locations, and penetration levels/sizes of PV plants and BESS units. Various power system models are also investigated in these studies. The classification of these studies is depicted in Figure 3 and further explained in the following sections.

Units

The literature shows more PV plant grid integration studies than BESS units. Very few studies consider PV plants and BESS units simultaneously in grid integration. With the increasing integration of renewable energy sources into the grid, studies on the effects of BESS units in the grid are increasing. In this way, the number of studies

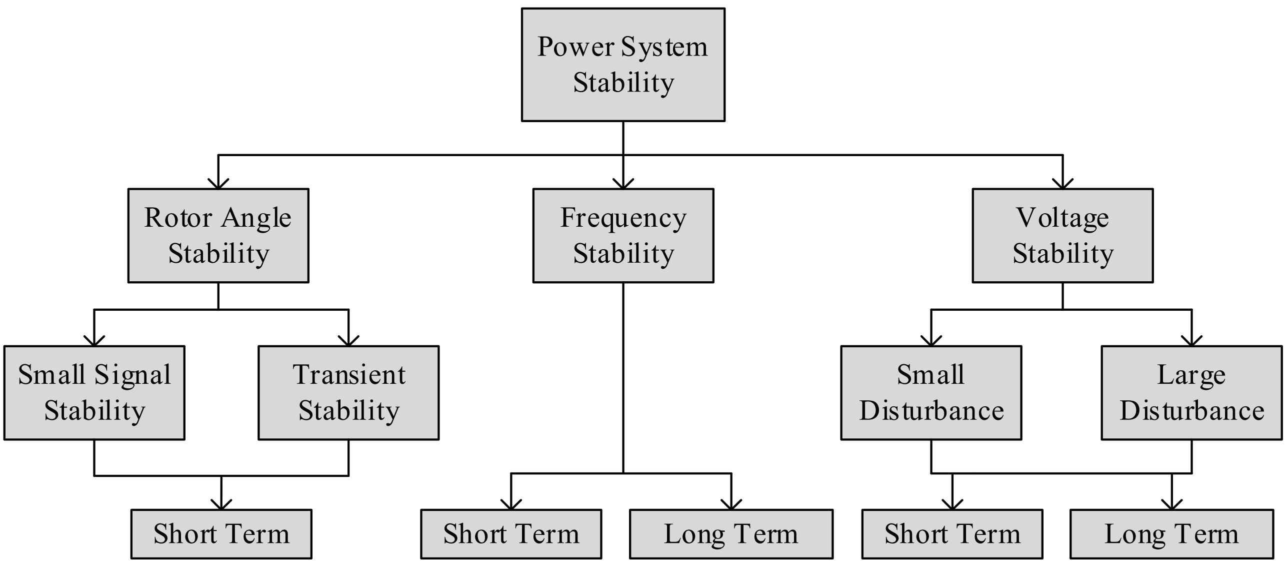


Figure 2. Classification of power system stability.

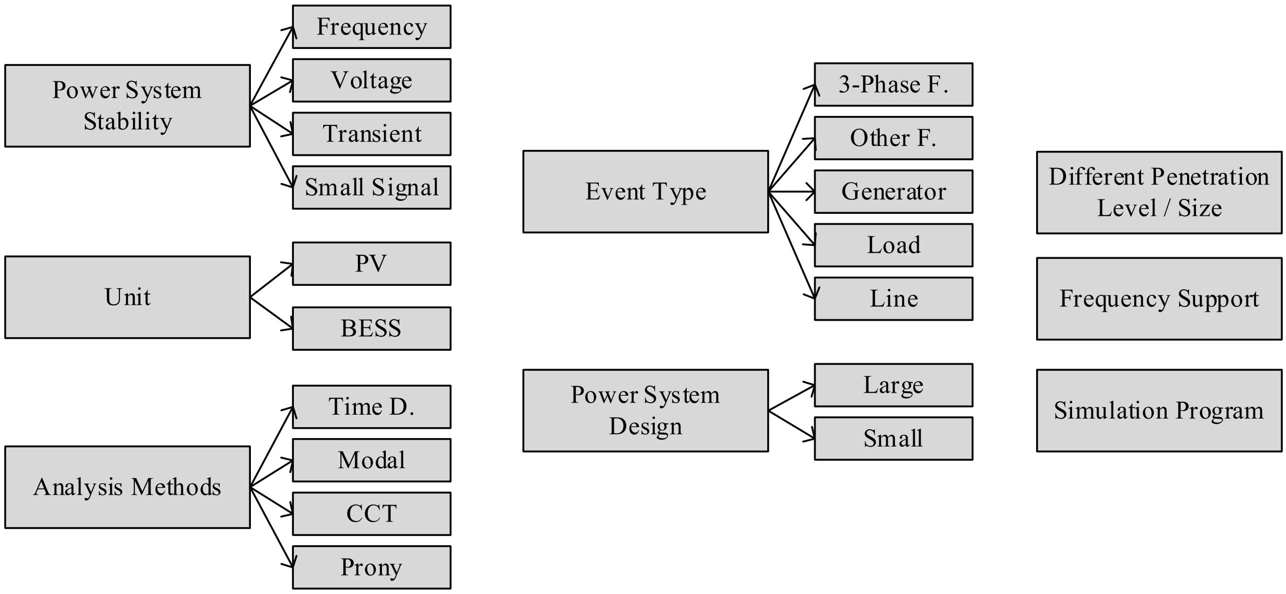


Figure 3. Classification of power system stability studies in the literature.

in which PV plants and BESS units are considered together will gradually increase.

While investigating the dynamic effects of PV plants on the grid, studies focus on low voltage ride through (LVRT), dynamic voltage support (DVS), and ramp rate. In [17], the researchers show that the use of LVRT and DVS can prevent voltage instability and the effectiveness of a ramp rate of 100% on stability. The researchers also compared local and centralized reactive power control methods on reactive power stability. In [18], researchers analyzed the impact on the voltage stability of the PV plant according to the German grid code. It shows the benefits of DVS and reactive power control methods. However, it also states that cost can be a limitation in this case.

The study [19] demonstrates how optimal BESS control enhances small signal stability, transient stability, and frequency stability. In addition, this study compares the BESS with the power system stabilizer (PSS) and demonstrates the success of the BESS in damping oscillations compared to the PSS. In [20], the optimum location for BESS units is studied to eliminate the detrimental effects of converter-based power generation units (such as wind and solar) on transient stability. In addition, short circuit faults are created at different locations, and the optimum BESS location is determined by using the magnitudes of voltage response and short circuit fault currents. In [21], BESS is compared with shunt capacitors and ultracapacitors. This comparison was made in terms of small signal stability and transient stability for two different power systems. It is shown that BESS units are more useful in thermal-dominated power systems and ultracapacitors are successful in hydro-dominated power systems.

In [22], the impact of PV plants and BESS on small signal stability and frequency stability in the grid is considered together. It is demonstrated that the combined use of PV plants and BESS can have a better impact on stability than synchronous generators. For a BESS in an integrated power system with PV plants, a new corrective voltage control technique is carried out in [23] to prevent long-term voltage instability. Through several scenarios employing models of the Scandinavian power system, the usefulness of the proposed approach has been confirmed. The research aimed to minimize the investment costs and voltage drops of the system by determining the optimum number, location, and capacity of BESSs. With the proposed approach, it was determined that PV plants can perform best with "plant-level Q and locally coordinated Q/V control.". For power systems integrating BESS, wind farms, and PV plants, [24] proposes a flexible wide-area multimode controller (MMC) based on the Firefly algorithm. It also shows that the proposed multimode controller can increase the utilization of renewable energy sources in the Java power system by up to 50%.

Analysis Methods

Power system stability analyses can employ various analysis methods. The most common and useful method among these is time domain analysis. Within this analysis, the evaluation of the system's fluctuations in frequency, voltage, rotor angle, active power, and reactive power prior to and following an abnormal occurrence is regularly compared. Another technique often used is modal analysis. Studies on small signal stability typically favor this method, which involves linearizing the model for small frequency oscillations [25, 26] . While investigating parameters such as eigenvalues, damping ratio, and participation factor, visuals such as mode shape and eigenvalue plot can be used. You can check the rotor angle stability using the critical clearing time (CCT) index and Prony analysis. When examining transient stability, the CCT index is generally used along with the time domain analysis. The CCT index can be applied to pinpoint critical moments in the system as well as to strengthen the analysis. The CCT index indicates the maximum time to address the fault without compromising system stability [27]. When examining small signal stability, Prony analysis is usually used alongside modal analysis. After a small change, Prony analysis finds the dominant modes' oscillation frequency, damping, and amplitude [28].

The authors in [28] perform both small signal stability and transient stability analysis for different penetration levels of the PV power plant. When performing Prony analysis for small signal stability, CCT is used to identify critical locations. Replacing the PV power plant with a synchronous generator enhances the transient stability for faults occurring at non-critical locations in the power system. However, the effect is found to be negative in critical locations. Depending on the proximity of the minor disturbance location relative to the power generators, the PV plant can engender both beneficial and negative outcomes for the small signal stability. In [29], researchers perform a small signal stability analysis with Prony analysis for a PV power plant using a model that takes solar radiation and temperature into account. Both CCT and time domain analysis reveal in [30] that replacing a synchronous generator with a PV plant and PV plant operating them in a voltage control mode can increase transient stability. [31] presents an analysis in terms of both voltage and transient stability by suggesting a control scheme for BESS. Using CTT and time domain analysis, it is determined that distributed BESSs yield better voltage stability results, while transient stability results remain relatively unchanged. In [32], the advantages of the proposed passivity-based control method, along with static synchronous compensators (STATCOM) and BESS, for the stability of the power system are discussed. According to the findings, the proposed approach enhances damping and provides improved transient stability performance.

Event Type

Various event types are used in stability studies in power systems. These event types consist of issues that commonly occur in power systems. In general, short-circuit faults and the sudden in-and-out-of-service of power system elements are dynamic issues encountered in power systems. While single-phase ground fault is the most prevalent form of short-circuit failure on the grid, investigations are usually centered on three-phase short-circuit faults rather than unbalanced faults, as it has the most powerful effect among short-circuit faults. In addition to short circuit faults, imbalances between generation and consumption are also frequently examined. These imbalances are addressed by disconnecting synchronous generators or loads.

Authors in [33] carry out stability analysis by replacing synchronous generators with PV power plants. In the study, the effect of plants in different locations at different penetration levels is analyzed while the PV active power generation for high and low load demands remains constant. The analysis is carried out for the disturbance of the line, generator, load, and three-phase short circuit faults. The authors in [34] propose a control method for PV power plant inverters to absorb a portion of the kinetic energy stored in the synchronous machine. The proposed control method attempts to regulate voltage by providing reactive power transfer. This study focuses on a two-phase ground fault and demonstrates the benefits of the proposed method on voltage and transient stability. In [35], the stability of the PV power plant is analyzed in case the power flow direction changes with the connection of the PV plant to the power system and the disconnection of the line. As a result of this analysis, it is revealed that the contribution of the PV plant to the fault current is low. In [36], the impact of PV plants with different penetration levels during line outage with PSS and BESS is also analyzed. Due to the lack of BESS connection, it is concluded that PSS alone does not meet stability criteria as the PV penetration rate increases. It is also found that BESSs closer to the generation units have a more favorable impact on stability. In [37] a different control structure for BESS is proposed and compared with conventional BESS and STATCOM. Different short circuit faults, line openings and load variations are considered. This system demonstrates the effectiveness of the proposed control structure for BESS in reducing oscillations when the upper power transmission limit is reached on tie lines without STATCOM installed. Authors in [21] use an improved Lyapunov Bases algorithm to analyze the voltage stability of BESS. The authors test the influence of BESS on stability by associating it with the critical bus during generator, load, and line outages. The authors uncover the constructive effect of BESS on voltage stability.

Structure of Power System

The quantity of buses is a fundamental element in the design of a power system structure for stability studies, and thus it is the number of buses that determines whether the system is considered small or large. It could be argued that the number of buses alone is not a sufficient measure to classify a system as small or large; however, when the power system elements (such as synchronous generators, loads, etc.) used in the studies are examined, such a classification can be accepted. A small power system can illustrate the reaction of the unit used in the analysis process. However, its impact on the system cannot be observed in sufficient detail. When conducting stability analysis and measuring the effect and responsiveness of a unit, it is therefore ideal to examine both small and large systems.

This section reviews key studies using two different-sized power systems (small and large), as positive results in a small system may not hold in a large one, necessitating multi-system testing for stability. In [38], the effects of DVS, LVRT, and ramp rate capabilities of PV plants on voltage stability and transient stabilization are analyzed. Initially, CCT is used to evaluate PV fault ride-through abilities in a small system, followed by tests in a large system where DVS effects on location are examined. Findings suggest that not using LVRT and maintaining a low ramp rate harm voltage stability, while a leading power factor and DVS capability mitigate this. In [39], a DVS method for active power support in PV plants is proposed, showing better voltage stability across systems compared to traditional methods. Study [40] examines a control method for PV plants, analyzing short- and long-term voltage stability using reactive power capability curves. Results indicate that PV plants offering long-term reactive support outperform synchronous generators, though stressed systems face both positive and negative effects on stability. Decreased temperature and solar radiation negatively affect long-term stability. Another study [41] proposes a BESS control strategy to enhance primary and secondary frequency control. Using a bode diagram, the transfer function is analyzed for frequency stability in both small and large systems. In a small system, BESS improves stability amid generation changes in wind power. In a large system, BESS stabilizes frequency against fluctuations from wind/solar generation and synchronous generator outages, demonstrating its efficacy for short- and long-term stability.

Different Penetration Level (PV) / Size (BESS)

The penetration level of PV power plants and the size of BESS units in grids are increasing day by day. To establish the future shape of the energy system and identify possible problems, stability analyses should be carried out at different levels of penetration and unit size (PV/BESS).

In [42], PV plants with different penetration levels are connected to a power system with gas and thermal units to reduce power flow and frequency deviations. The study shows that the PV plant has the least negative impact on stability in systems with non-reheated thermal units. In [43], PV plants were replaced by non-critical synchronous generators at various penetration levels. At low penetration level, the effect of this replacement on stability is favorable, while the opposite occurs at high penetration level. In [44] and [45], the studies examine PV units as rooftop (distributed) and centralized units (centralized) and show that the bus voltage increases with PV penetration up to a point where stability starts to decrease. The studies also show that centralized PV plant outages affect frequency stability more severely than rooftop PV outages. In [46], the penetration levels of high PV plants are analyzed and the P-V and P-Q modes for the utilization of the plants are compared. It is found that the P-V mode improves voltage stability but negatively affects the frequency stability compared to the P-Q mode. In [47] and [48], it is shown that the damping of oscillations decreases as PV penetration in the grid increases. It is also shown that high PV penetration levels (up to 65%) can significantly affect frequency stability in US grids. In [49], it is also verified by transient and small signal stability analysis that high PV penetration levels reduce system damping. In [50] and [51], the effects of PV plants on stability were analyzed without removing synchronous generators from the grid. It is shown that PV plants show negative effects on stability as the penetration level increases. In [52], it is also shown that the integration of PV plants into the grid has a positive effect on stability at the beginning but has negative effects as the penetration level increases. In [53], BESS is tested to prevent grid disconnection during disturbances and shows that appropriately sized BESS can prevent grid disconnection and load shedding. In [54], the optimal BESS size and location are addressed to mitigate the impacts of PV plants at high penetration. In [55] and [56], it is shown that BESS delay time significantly affects frequency stability and distributed BESS is more effective for stability than centralized structure. In [57] and [58], BESS sizing for frequency support under high PV penetration is discussed. They show that droop-controlled BESS can improve the frequency response in low inertia systems, and high sag coefficients are more helpful for damping and stability.

Frequency Support

When PV power plants are used in power systems, certain grid codes require frequency support, while others do not. Due to the increasing penetration level of the plants, frequency support becomes inevitable. This situation has been taken into consideration in a few studies in related literature. In this section, in addition to PV power plants that provide frequency support, studies on the parameters of BESSs for frequency support are investigated. In [59], have analyzed the effect of PV power plant (central control) on frequency stability to provide frequency support. In the study, the load is altered to investigate the impact of the plant's moment of inertia emulation control parameter on frequency stability. Similarly, [60] investigates frequency stability underload changes for PV plants with local frequency support control. In [61], various control methods are discussed, and it is shown that these methods can mitigate the negative effects of high PV penetration levels in the grid. In [62], it is shown that the impact of centralized frequency support controls on power system stability is significant, especially for various faults such as short circuits and line outages. [63] analyzes the inertial response of BESS for frequency stability across disturbances of varying sizes, emphasizing the importance of BESS size and location. Study [64] compares detailed and average BESS models, revealing that while both perform similarly within control limits, the detailed model is preferable for stability when limits are reached. In [65], BESS effects on frequency stability are examined during synchronous generator outages, showing that optimizing the inertial emulation controller's gain is critical for stability and SOC management. [66] suggests a novel approach to multiple linear regression analysis for calculating the de-loading % of PV systems according to frequency response. According to the results obtained, it has been determined that as PV integration increases in the grid, PV systems provide frequency stability by maintaining the required offload percentage. For PV systems that control active power demand, a novel method based on frequency regulation through reactive power control (FRQC) is presented in [67]. To temporarily lower the demand for the electrical power supplied by synchronous generators, the suggested FRQC method coordinates changes in reactive power. The analyses demonstrate that the suggested FRQC scheme enhances both the system frequency stability and the post-fault frequency trajectory. In [68], proposes management plans to boost PV hosting capacity and fixes to enhance the delivery of frequency support services using flexible energy sources. The findings indicate that by lowering the on-load tap changer setting value, the grid's PV hosting capacity may be enhanced. Additionally, by charging the BESS concurrently during steady-state operation, the PV host capacity with BESS on the PV connection point can be increased while preventing local over voltages.

Simulation Programs

Various simulation programs are used to perform stability analysis in power systems. In a survey conducted with transmission and distribution operators, it was reported that the two most used programs for power system stability analysis are Power System Simulator for Engineering (PSS/E) (41%) and DigSilent (13%) [69]. In addition, it was found in the review of the literature that MATLAB (33%), DigSilent (33%), and PSS/E (14%) are the programs used for power system stability analysis.

The parameters used for a given BESS model were tested in the simulation programs DSA Tools PSLF, PowerWorld, and PSS/E by the authors in [70] , and the outcomes were analyzed. In this way, both the model and the programs were validated and tested. The effect of the model on frequency and voltage stability was analyzed.

RESULTS AND DISCUSSION

The penetration level of PV units and other renewable energy sources with converters in the power system is becoming more widespread globally each day. The lack of inertia in these generation units, coupled with their intermittent generation capabilities, negatively impacts the stability of power systems. To eliminate such negative effects, generation units with converters should support voltage and frequency. Also, a portion of the energy generated should be stored. This is why BESS is gaining popularity with grids as a reliable means of ensuring the stability of the power system. This paper reviews the current state of PV power generation and BESS usage worldwide and their impact on stability. Additionally, the characteristics of PV plants and BESSs outlined in academic studies on power system stability, along with the study results, are discussed. Table 5 presents an overview of the reviewed studies for PV and BESS units.

The literature summary provided in Table 5 is presented in statistical format in Figure 4. In Figure 4, the total proportion of groups may exceed 100%. For example, a study may analyze both frequency and voltage stability. For this reason, the total values under the heading of power system stability exceed 100%. The ratios obtained under different penetration level/size and frequency support headings are evaluated separately for PV and BESS studies. For instance, 57.45% of the studies that included PV plants investigated different penetration levels.

As seen in the figure, frequency stability is prominent in most studies. Studies on BESS units have increased with their integration into the grid in recent years, and PV plants are more frequently included in studies. The figure shows that time-domain analysis is performed in almost all power system stability studies. Although three-phase short-circuit faults are generally selected for stability studies, other disturbance effects are also frequently preferred. However, other faults, which refer to unbalanced faults, are not frequently addressed in stability studies. The figure shows that the use of large and small systems in stability studies is nearly equal. Studies on different BESS sizes are not as common as those on PV plants, while different penetration levels are widely considered in PV plant studies. Studies on the frequency support of PV plants are not widely discussed, although they have started to become widespread in recent years with the integration of large PV plants into the grids.

The findings obtained from the classifications made in this study can be summarized as follows.

- The analysis of the literature shows that investigations are carried out on PV and BESS units for different stability analyses of the power system. It is observed that most studies are primarily based on the analysis of frequency and voltage stability. In addition, based on the findings of the related studies, it can be argued that examining different types of stability analyses together is the most sensible approach, as a situation that may appear beneficial in one such analysis may present a negative outcome in another.
- It is seen that PV power plants and BESS units are rarely used together in power system stability studies.
- It can be stated that modal and time-domain analyses are frequently preferred. The use of various stability analyses can make the results more interpretable and clearer.
- Examining the types of events used for analysis, it is seen that load events and three-phase short-circuit faults are generally preferred. Frequency stability analysis is commonly executed in the case of a load disturbance. Three-phase short-circuit faults are used for frequency, voltage, and transient stability analysis. It can be noted

Table 5. Summary of the studies in literature

Citation Number	Power System Stability				Unit		Analysis Methods				Event Type					Power System Design		Dif. Penetration Level (PV) / Size (BESS)	Frequency Support	Simulation Program
	Frequency	Voltage	Transient	Small Signal	PV	BESS	Time Domain	Modal	CCT Index.	Prony	3-Phase Fault	Other Faults	Generator	Load	Line	Large	Small			
[17]	✓	✓	✓		✓		✓		✓		✓				✓	✓				D
[18]		✓			✓		✓		✓		✓						✓			D
[19]	✓		✓	✓		✓	✓	✓						✓			✓		✓*	M
[22]	✓			✓	✓	✓	✓	✓								✓			✓*	M
[20]			✓			✓	✓				✓					✓			✓*	D
[21]		✓				✓	✓						✓	✓	✓	✓			✓*	P
[23]		✓			✓	✓	✓				✓		✓		✓	✓			✓*	D
[24]	✓		✓	✓	✓	✓	✓	✓			✓		✓			✓		✓	✓**	
[28]			✓	✓	✓		✓	✓		✓	✓					✓		✓		D
[29]			✓	✓	✓		✓	✓		✓						✓		✓		M
[30]		✓	✓		✓		✓		✓		✓						✓	✓		D
[31]		✓	✓			✓	✓		✓		✓					✓			✓*	
[32]		✓	✓	✓		✓	✓	✓	✓		✓			✓		✓			✓*	M
[33]	✓	✓		✓	✓		✓	✓			✓		✓	✓	✓	✓		✓		M
[34]		✓	✓		✓		✓					✓			✓		✓			M
[35]		✓	✓		✓		✓				✓				✓		✓			PA
[36]	✓	✓			✓	✓	✓					✓		✓	✓		✓		✓*	
[37]	✓	✓				✓	✓				✓	✓		✓	✓	✓			✓*	
[38]		✓	✓		✓		✓		✓		✓					✓	✓			
[39]	✓	✓	✓		✓		✓		✓		✓					✓	✓			
[40]		✓			✓		✓				✓				✓	✓	✓	✓		D
[41]	✓				✓	✓	✓						✓	✓		✓	✓	✓*	✓*	D
[42]	✓			✓	✓		✓	✓						✓			✓	✓		M
[43]	✓	✓	✓	✓	✓		✓	✓			✓		✓	✓	✓	✓		✓		PW
[44]	✓	✓	✓		✓		✓				✓				✓	✓		✓		DT
[45]	✓	✓		✓	✓		✓	✓	✓		✓					✓		✓		DT
[46]	✓	✓			✓		✓						✓			✓		✓		P
[47]	✓			✓	✓		✓	✓			✓					✓		✓		
[48]	✓				✓		✓						✓			✓		✓		
[49]	✓		✓	✓	✓		✓	✓		✓	✓					✓		✓		DT
[50]	✓	✓			✓		✓				✓					✓		✓		P
[51]		✓	✓		✓		✓				✓					✓		✓		N
[52]	✓	✓	✓		✓		✓		✓		✓						✓	✓		M
[53]	✓					✓	✓								✓	✓		✓*	✓*	
[54]	✓				✓	✓	✓						✓			✓		✓**	✓*	M

Table 5. Summary of the studies in literature

Citation Number	Power System Stability				Unit		Analysis Methods				Event Type					Power System Design		Dif. Penetration Level (PV) / Size (BESS)	Frequency Support	Simulation Program
	Frequency	Voltage	Transient	Small Signal	PV	BESS	Time Domain	Modal	CCT Index.	Prony	3-Phase Fault	Other Faults	Generator	Load	Line	Large	Small			
[55]	✓					✓	✓							✓		✓		✓*	✓*	D
[56]	✓					✓	✓							✓		✓	✓	✓*	✓*	
[57]	✓	✓			✓	✓	✓						✓			✓		✓**	✓*	D
[58]	✓					✓	✓						✓	✓		✓		✓	✓*	
[59]	✓				✓		✓							✓			✓		✓	
[60]	✓				✓		✓							✓		✓			✓	D
[61]	✓				✓		✓							✓			✓	✓	✓	
[62]	✓	✓		✓	✓		✓	✓			✓		✓	✓	✓	✓		✓	✓	D
[63]	✓					✓	✓							✓			✓		✓*	D
[64]	✓					✓	✓				✓		✓				✓		✓*	M
[65]	✓					✓	✓						✓	✓			✓		✓*	D
[66]	✓				✓	✓	✓						✓			✓		✓	✓**	D
[67]	✓		✓		✓	✓	✓							✓		✓		✓**	✓**	D
[68]	✓	✓			✓	✓	✓							✓		✓			✓**	PC
[70]	✓	✓				✓	✓				✓		✓		✓	✓			✓*	X
[71]	✓	✓		✓	✓		✓	✓					✓	✓		✓		✓	✓	
[72]	✓					✓	✓						✓		✓	✓		✓*	✓*	M
[73]	✓					✓	✓							✓		✓			✓*	M
[74]	✓					✓	✓						✓			✓			✓*	P
[75]	✓				✓		✓							✓		✓		✓	✓	D
[76]	✓				✓		✓							✓		✓			✓	D
[77]	✓				✓		✓							✓			✓		✓	
[78]	✓	✓	✓		✓		✓				✓						✓	✓		
[79]	✓			✓	✓	✓	✓	✓						✓		✓			✓*	M
[80]	✓					✓	✓							✓			✓		✓*	
[81]	✓	✓				✓	✓					✓				✓		✓*	✓*	D
[82]	✓	✓				✓	✓							✓		✓		✓*	✓*	D
[83]		✓		✓	✓		✓	✓							✓	✓		✓		M
[84]		✓	✓		✓		✓					✓		✓		✓				E
[85]		✓	✓			✓	✓		✓		✓				✓	✓			✓*	
[86]			✓	✓	✓	✓	✓	✓			✓					✓			✓*	
[87]			✓			✓	✓				✓				✓	✓			✓*	P
[88]			✓		✓		✓				✓				✓		✓	✓		PW
[89]				✓		✓		✓									✓		✓*	
[90]				✓		✓		✓								✓			✓*	
[91]				✓	✓		✓	✓			✓					✓		✓		DT

✓* only BESS, ✓** PV+BESS

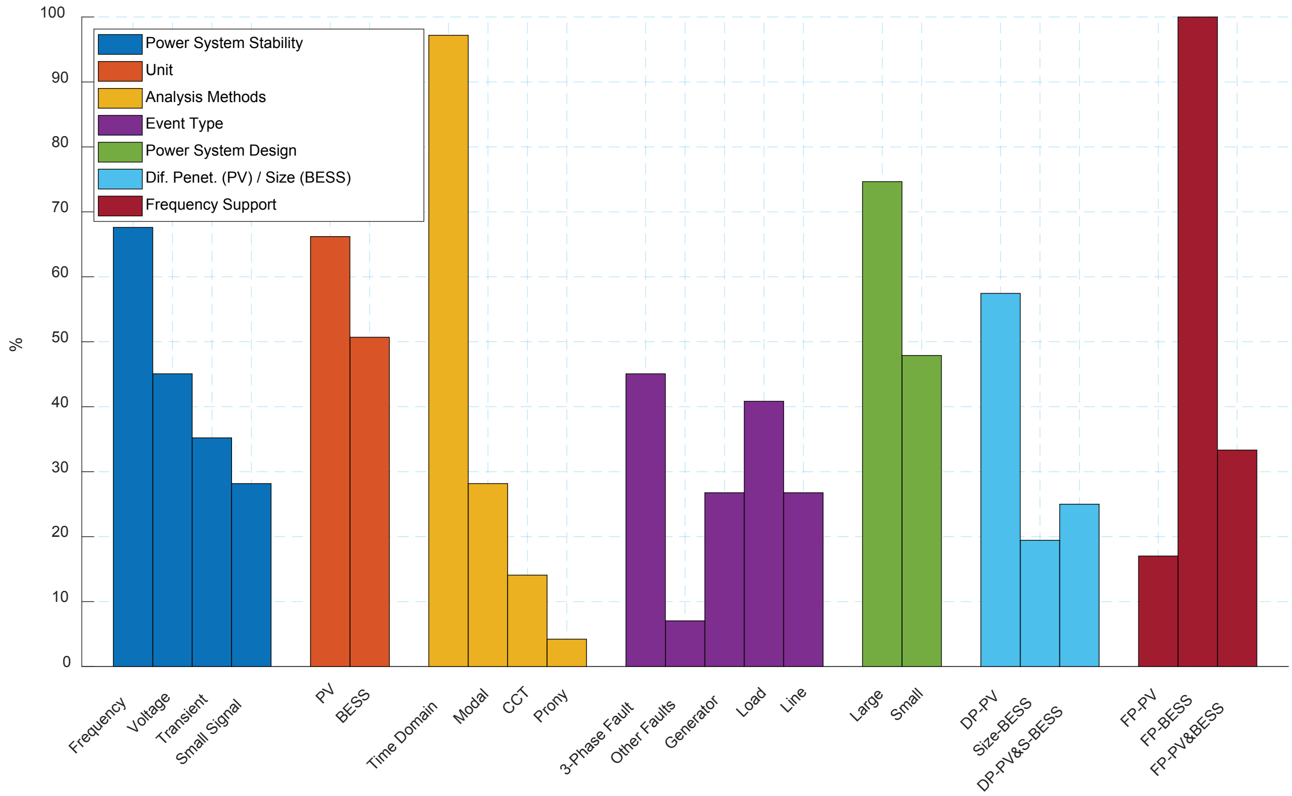


Figure 4. Statistical analysis of literature summary.

that, in most studies, line openings are conducted following a short-circuit fault.

- It is seen that large power systems are usually the ones where stability analyses are conducted. However, studies involving both small and large power systems are rare. Nevertheless, by using both, the effects of PV and BESS units and their responses to changes can be observed more clearly.
- It has been observed that different PV power plant penetration levels are frequently examined in terms of stability analysis. These studies can be roughly divided into two groups based on the integration of PV power plants with or without synchronous generator replacement. Additionally, when looking into the size of a BESS, its location is usually considered. As the penetration of PV plants increases, the negative impact on power system stability also increases. This effect can be mitigated by using BESS units of different sizes. However, in literature, studies focusing solely on the size and location of BESS in the power system are generally included.
- As the penetration of PV power plants in power systems has increased, the need for frequency support has become more important. Literature has evaluated this phenomenon and examined the effect of PV power plants on frequency, as well as different control methods. Additionally, examining the impact of control systems and parameters on frequency support has been a recurrent topic of research for BESS.
- It can be stated that studies typically involve the use of DigSilent PowerFactory and MATLAB simulation programs, with PSS/E being more popular among transmission and distribution operators.

CONCLUSION

In this study, the effects of PV power plants and BESS on power system stability were examined using a literature-based and systematic approach. Within the scope of the study, existing research was classified and compared under headings such as stability type, unit type used, analysis method, event/fault type, system scale, PV penetration level and BESS sizing, frequency support approach, and simulation tools. This comprehensive evaluation revealed that the literature focuses particularly on frequency and voltage stability; time domain analysis is the most common method; events such as three-phase short circuits and load changes are frequently preferred; and tools such as DigSilent PowerFactory and MATLAB are prominent. However, it was observed that the number of studies addressing PV and BESS together is limited, with many studies evaluating these two structures separately, creating a significant gap, especially for systems with high renewable penetration. In this regard, the study not only summarizes the literature but also clearly highlights which topics have been intensively studied in terms of power system stability and which areas require further research.

The findings indicate that as the share of PV plants in the grid increases in line with climate change mitigation, rising electricity demand, and economic energy production targets, BESS integration has become critical in terms of stability. This situation necessitates a reassessment of existing grid policies, integration plans, grid codes, and, in particular, frequency response protocols. New regulations are needed to define performance requirements for the safe and effective integration of PV and BESS into the grid, encourage investment, and guarantee stability at high penetration levels. Furthermore, the dependence of these systems on digital infrastructure for real-time monitoring and control increases their vulnerability to cyberattacks; therefore, it is crucial that future studies address cybersecurity, secure communication infrastructure, data integrity, and system resilience alongside stability analyses. In addition, increasing the number of studies that evaluate PV and BESS together, examining the effects of different battery chemistries on transient stability, determining the necessary BESS scaling strategies at high PV penetration, and researching the effects of distribution/transmission operators' grid codes on stability stand out as priority research areas for future studies.

AUTHORSHIP CONTIBUTIONS

Çavdar, B.: Writing, Reviewing, Editing and Visualization. **Karaca, E:** Writing, Reviewing, Editing and Visualization. **Okumuş, H:** Writing, Reviewing, Editing and Visualization **Nuroğlu, F. M:** Supervision, Writing, Reviewing and Editing.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

ABBREVIATION

BESS	battery energy storage system
CCT	critical clearing time
DVS	dynamic voltage support
EI	eastern interconnection
ERCOT	electric reliability council of Texas
FRQC	frequency regulation through reactive power control
GDP	gross domestic product
LVRT	low voltage ride through
MMC	multi-mode controller
PSCAD	power systems computer aided design
PSS	power system stabilizer
PSS/E	power system simulator for engineering
P-Q	power factor control
P-V	voltage control
PV	photovoltaic
SOC	state of charge
STATCOM	static synchronous compensator
WECC	western electricity coordinating council

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