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Frequency stability analysis of power grid during photovoltaic generation in Hail region (Arabia Saudi)

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Increases in power generated by renewable energy sources (RES) that suffer from low-moment inertia could be hazardous to the power system's capability to operate reliably and consistently. Because RESs do not have rotating parts, their penetration into modern power systems may result in a reduction in the system's inertia, which is directly related to the power grid stability issue. This reduction in rotational inertia associated with synchronous generation may increase the rate of frequency changes, reducing frequency control performance. It is important to investigate frequency stability under disturbances in such systems. The main objective of this research is to evaluate the technical viability of supplying an inertial response in power grids with high photovoltaic (PV) power penetration utilizing energy storage devices based on batteries. The case study of this work includes a 147.9 kWPV system connected to the national power grid of Hail City, which is located in the north of Riyadh, the capital of Saudi Arabia. In this paper, batteries are recommended to improve the stability of the frequency. The inertia of the proposed system varied via adjusting the penetration degree of RES. This evaluation was carried out using the voltage source inverter model under droop control. A detailed model provincial power network is built using MATLAB/Simulink to assess the effects of large-scale penetration of RES on frequency stability. Two important points that will distinguish our study from the other studies that use droop control inverters and battery systems are the same model.

KEYWORDS

frequency stability analysis, photovoltaic generation, Hail region, energy storage devices, MATLAB/Simulink

1 Introduction

The main challenge of achieving large-scale penetration of RES in a microgrid is minimizing system inertia (Hasan and Chowdhury, 2022). In a normal power system, the overall system inertia is mostly linked to the rotating mass of synchronous generating units. This inertia helps keep the frequency stable by opposing any changes in the frequency of the system (Fern´andez-Guillam´on et al., 2020). However, because they are connected to the power grid via a DC power converter interconnection, most RES do not provide any intrinsic inertial support. As a consequence, the system's overall inertia falls as the amount of renewable energy grows, increasing its susceptibility to frequency instability challenges (Phurailatpam et al., 2021; Zhang et al., 2022).

A high Rate of Change of Frequency (RoCoF) brought on by a decrease in overall inertia results in a sudden rise or fall in frequency as well as a larger frequency variation

(Fernández-Guillamón et al., 2020). These circumstances may set off load-shedding relays and RoCoF, and in the worst scenario, they may lead to a cascade trip of all generators and a total system shutdown. In traditional systems with enough synchronous generation, the absence of enough inertia has not been a significant problem, but in RES-integrated systems with declining inertia, it has grown to be a growing worry (Pepiciello et al., 2020). Consequently, system operators and grid planners must have a precise estimate of the net available inertia in the power network. With a precise assessment, suitable defenses may be created against frequency stability's difficulties. Based on the level of system inertia, such steps may involve the deployment of acceptable frequency confinement reserves and the implementation of adequate virtual inertia sources (Huang et al., 2020; Pratap et al., 2021). It is significant to highlight that IIRES: Inverter-Interfaced Renewable Energy Source (that connect renewable sources with DC (Direct Current) sources such as PV, wind, etc. to the AC (Alternating Current) power grid), in addition to ESS-like batteries, are anticipated to have a significant role by offering virtual inertia assistance in order to overcome the issue of low system inertia (Li et al., 2019; Zdiri et al., 2019). The density will rise if the ESS is integrated into the power system, which will improve the power system's ability to respond quickly to disruptions. is For power system-level research, the power swing equation approach to power system inertia estimation is mainly utilized to evaluate the equivalent inertia constant (H) when the frequency varied for a specified disturbance is measured (Kpoto et al., 2019). Synchronous inertia is the intrinsic inertia that is only produced by the kinetic energy (KE) contained in the spinning mass of the synchronous generators, as the name indicates. Through a rotating magnetic field, these sources' rotational speed is electromagnetically linked to the system's frequency, allowing for immediate power variation during a frequency disturbance. Another significant concern is the accuracy of the synchronous inertia estimation using traditional approaches, given the rising penetration of RES and virtual inertia support. In general, the rise of renewable energy sources does come with some technological challenges. For example, (a) changes in power output, (b) fewer or no turbines for energy balancing (no hot reserve margin), and (c) less inertia because RESs use converters to disconnect from the traditional grid (Sami et al., 2020). The Battery-Energy Storage System (BESS) and the Supercapacitor-Energy Storage System (S-ESS) with power converters and PV panels with varied sunlight intensity are all featured in this work on the development of a Hail power system utilizing MATLAB Simulink software. A droop control inverter is used, which is crucial for maximizing frequency responsiveness. Inverters and other parts need to be linked to the electrical system in order to produce RESs. Since inverters do not have any spinning components that produce inertia, they are zero-inertia systems (Maulidhia et al., 2022). This literally indicates that, like with hybrid grids, the inverter's frequency lowers in response to an increase in the active power demand. It has been demonstrated that this technique contributes to the frequency response's dynamic nature and offers virtual inertia (Afshar et al., 2020). There is importance to adding batteries to solar systems, as they contribute to the continuity of supplying the consumer with electrical energy and improving the quality of electricity. Systems that do not contain battery systems suffer from a lack of reliability and stability. In addition to what was mentioned above, the importance of batteries in systems not connected to the grid lies in further improving the frequency level during disturbances, improving its level, and reducing the time to return to the original frequency as much as possible.

The irradiation (the sunlight intensity) and temperature, which are utilized as the input of the PV system, are real values of the Hail region. The following will be a description of the structure of this written work: This section describes the issue of the impact of the RES on the frequency variation, followed by remarks about the system's goals and approach in the introductory part. In Part 2, the phases of frequency response control will be discussed.

This paper will give a clear vision of frequency response during disturbances (in the case of a rapid increase or decrease in load or generation). The operators or planner engineers of power systems can benefit from this study for the purpose of controlling the frequency and keeping it within permissible limits during disturbances. The study of the impact of the PV system on grid stability can be applied to other large systems with larger capacities to observe this effect, as this study presents the amount of decline in frequency under certain conditions.

The RES's Virtual Synchronous Generator (VSG) and the inertia simulation are both included in Part 3. Part four provides a description of the inverter's droop control approach. Section 5 will detail the case study and the suggested MATLAB Simulink software implementation of the microgrid. The conclusions will appear in Section 6 at the end.

2 Power system security under RES penetration

Instead of using traditional generation units in past years, RES has been utilized to reduce carbon dioxide emissions. The much more common type of RES used and the connecting concepts of photovoltaic power plants are different from those of conventional power plants in a number of ways. One of the most obvious differences is that there are not any spinning parts to store inertia that can be used to weaken the power system during power outages. This makes the power system weak and hard to keep up in emergency situations. Large-scale solar power plants' power system security evaluations are concerned with how the system can continue to function within allowable operational parameters despite these disruptions. In comparison, power system security can be defined as the system's ability to withstand the effects of an outage or interruption for any system component brought on by disturbances and quickly resume regular operation (Li et al., 2020; Zhang et al., 2023). Static security is used to evaluate the bus system voltages and the equipment's thermal limit violations after the contingency, and dynamic analysis is used to ensure that the equipment keeps running within its operational constraints (Huang et al., 2018). System stability indices such as voltage stability, frequency stability problems, or angular stability are the focus of dynamic analysis.

3 Levels of response frequency control

Figure 1 shows the normal frequency fluctuation during a power outage as well as the essential management measures to lessen its

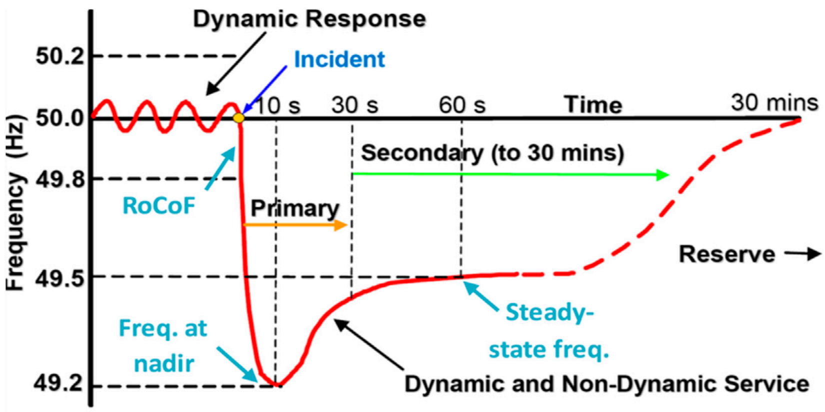

FIGURE 1
Frequency response levels (Akram et al., 2015).

effects. The first step is the synchronous machines' natural reaction (sometimes referred to as IR Inertia Response), in which the synchronous generators fight the frequency drop by releasing the stored KE in spinning masses. The principal frequency control, which maintains the frequency of the new steady-state value, comes after this stage (Liu et al., 2023). Subsequently, the load frequency management phase employs the PI regulator, as in the second stage, to return the frequency to its rated value.

Since they affect the frequency of nadir and RoCoF, the timing and size of the first two stages are crucial. The last phase, known as tertiary frequency control, deals with manual operation control. The levels listed below are the main levels of frequency control in the power system during disturbances.

In their revolving components, traditional generators store KE. This energy is immediately released or absorbed during a perturbation; the system's initial frequency responsiveness is improved as this energy is instantly released or absorbed. There will be a mismatch in the torques operating on the rotors of the generators whenever a generation-demand mismatch happens, which will cause acceleration or slowdown. The inertia constant (H) is commonly used to characterize the stored KE in a generator as a ratio of its VA (Volt–Ampere) rating. It may be described as the amount of time period that can be given in seconds, needed for a machine to replenish its kinetic energy in case of working at its rated output power and their rated speed (Tielens and Van Hertem, 2012).

The swing equation it can be is presented in Eq 1 (El-Shennawy et al., 2018) as follows:

$$\frac{2H}{w_0}\frac{dw}{dt} = P_m - P_e - K_d\Delta w \quad (1)$$

The damping coefficient K_d is often disregarded during analyses of brief periods of time, like the period immediately after aftershocks. As a result, we have the straightforward form of (1), and the swing equation can be given as in Eq 2 (El-Shennawy et al., 2018):

$$\frac{2H}{w_0}\frac{dw}{dt} = P_m - P_e = \Delta P \quad (2)$$

The mechanical and electrical powers of the machines are (P_m) and (P_e), respectively, in p. u. while (W_0) and (W) represent the nominal and mechanical speeds that can be given in rad/sec. The stored KE on the stated machine capacity in VA is comparable to (H), which would also be given in a sec. Eq. 2 makes it evident that, for a given power imbalance, the (RoCoF) decreases as system inertia increases. This prevents the RoCoF relays put in the system to combat islanding operations from malfunctioning. Relays rely on the assumption that when islanding happens, there will be a significant imbalance between local generation and demand, leading to a large RoCoF. This would go beyond the relay set value, forcing them to disconnect the majority of the deployed distributed generation in the system for safety. In addition to decreasing RoCoF for load violations, high system inertia gives synchronous generators as well as other controllers additional time to respond. As a result, the maximum frequency change value, f, is decreased.

3.1 Primary and secondary stages of control systems

Primary and secondary frequency control systems are the two automated control systems that are included in traditional power plants. A primary control system is present in every unit. Primary control is the turbine speed variation to any frequency fluctuation in the system, which happens immediately. It is given shortly after the deviation, generally around 30 s (Fahad et al., 2020). The governor lowers, but does not approach zero, the frequency variation that will be experienced following a frequency event. As a result, the frequency stays within operating limits until the secondary control system operates. Mostly in the disturbance area, a secondary frequency control system using a PI controller takes place. It tries to get back to the nominal frequency of the system. It begins around 30 s after the divergence and lasts for a period of minutes.

3.2 Tertiary stage of the frequency control

During the tens of minutes to a couple of hours following a disruption, the sent-generating machines are manually altered during the tertiary frequency control step. The primary and secondary reserves are intended to be restored during this manual control stage (Fahad et al., 2020).

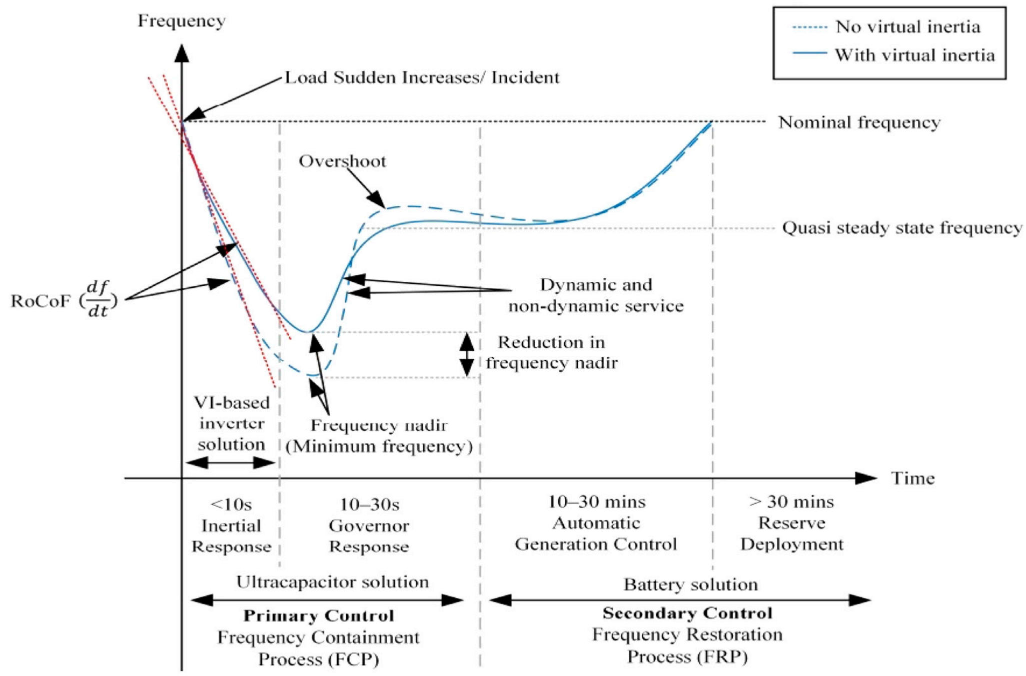

FIGURE 2
Virtual inertia impact.

4 Virtual inertia Emulation's

The virtual synchronous Machine (VSM) approach was introduced by Beck and Hesse in early 2007 (Beck and Hesse, 2007). It helps the electric grid by simulating a few of the characteristics of synchronous generation using power electronics, also called "virtual inertia emulation." As the amount of renewable energy grows, the inertia of the power system decreases. To deal with this, the VSM scheme was created to control power converters in a way that mimics the synchronous machine's inertia and other features (Rezkalla et al., 2018; Yang et al., 2023). Using an integrated strategy of controller design, power electronics, RES, and EES technologies, VSM can simulate the inertia of a traditional power network. Whereas the execution of every topological design differs, the concept of representing virtual inertia is the same for all layouts. In certain designs, distributed generation responds to fluctuations in the frequency of utility grid systems.

To address the low inertia issue, the approach of virtual inertia emulation/control is currently presented (Kerdphol et al., 2018). This control approach will virtually provide the inertia power needed by ESS for community-based high RES penetration, hence eliminating instability and power outages. Several attempts are currently being made to simulate virtual inertia using various control strategies. The reference (Liu et al., 2016) suggests comparing virtual inertia emulation and droop control systems for simulating inertia in the community. While in ref (Van De Vyver et al., 2016), we developed a droop technique to simulate virtual inertia in a wind power system. (Thiesen et al., 2016). described an inertia emulation approach for replacing the available inertia in the European community. In (Chen et al., 2017), DC microgrid-based virtual inertia emulation technologies are used in a community.

Virtual inertia emulation's main goal is to replicate the spinning inertia impact that traditional synchronous machines have on the stability of the power system. It has been possible to simulate the rotational inertia that can be given by RES in a variety of ways. Control measures are put into place for a specified time period to balance the generation and load for frequency regulation, as illustrated in Figure 2.

The graphic illustrates the key contrast between systems using virtual inertia and those that do not. The virtual inertia power grid has the following advantages (Yung Yap et al., 2019).

a) Reduction in the frequency's nadir and deviation from its steady state frequency (fn).
b) An increase in the frequency's transient or response times; and c a reduction in the frequency's overshoot.
c) A gradient with less incline and RoCoF.
d) Less time is required to return to the regular frequency.

In this work, the proposed system consists of a three phase inverter control that is designed based on droop control to improve the frequency response. In addition, ESS is used as inertia support for the system during faults and/or disturbances.

5 Droop control

Virtual inertia may be introduced to distributed generators by combining a power electronic converter with an algorithm for regulation and short-term energy storage. Whenever an inverter together with a controlling technique is utilized, it functions as a true synchronous generator; this type of device is known as a VSG

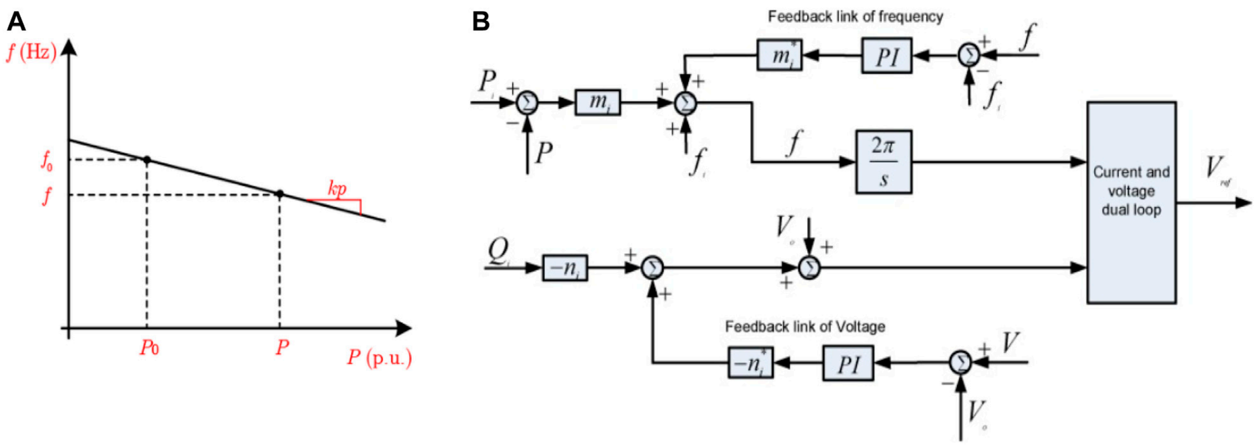

FIGURE 3
(A) (P-f) droop relationship curve, **(B)** The block daigram/droop control.

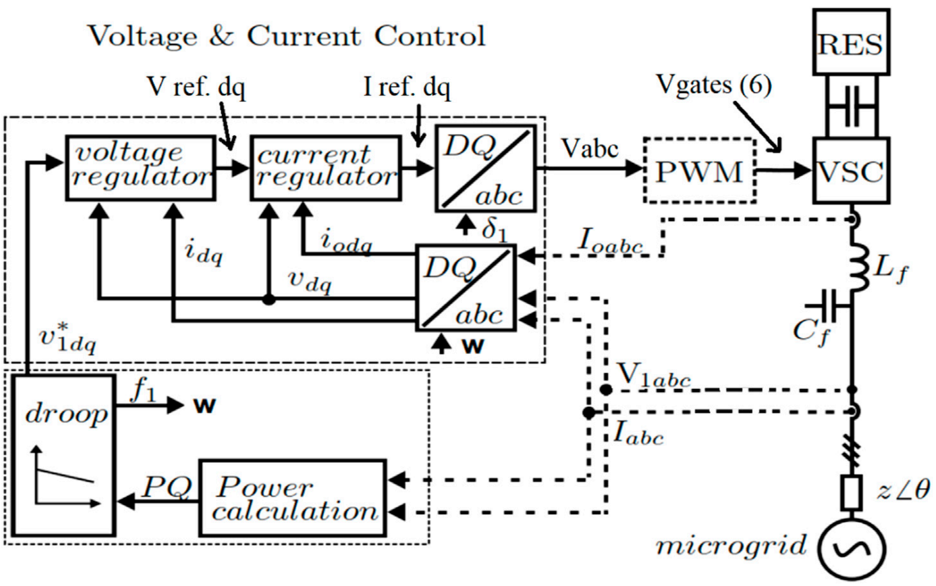

FIGURE 4
Droop control strategy of the inverter (Alghamdi and Cañizares, 2021).

(Pimprikar et al., 2018). To provide the ideal output response, the inverter control should incorporate synchronous generator properties. During normal operation, a synchronous generator's excitation regulator and turbine oversee and manage the output voltage and frequency, respectively.

Whereas the excitation control mechanism controls reactive-power as well as voltage, the generator control system has the capacity to control real output power as well as frequency (Oflr et al., 2018).

The main difference between a VSG and a synchronous generator is that a VSG does not need mechanical or electro-hydraulic governors and excitation controllers. The power-frequency (P-f) controller is designed based on the layout of the generator governor. Depending on the power characteristics of the generating unit, the governor controls the output frequency of a synchronous generator. The generator's frequency and its speed are related. To control the synchronous generator speed, the governor changes the prime mover's input power. Figure 3A depicts the power-frequency performance curve. To simplify the study, straight lines are used rather than curves. Figure 4B depicts the block diagram for the power-frequency droop control.

Equation 3 may be used to calculate the gradient of the P-F characteristic (Oflr et al., 2018):

$$m = -\frac{f_{2-} f_1}{P_{2-} P_1} = -\frac{\Delta f}{\Delta P} \tag{3}$$

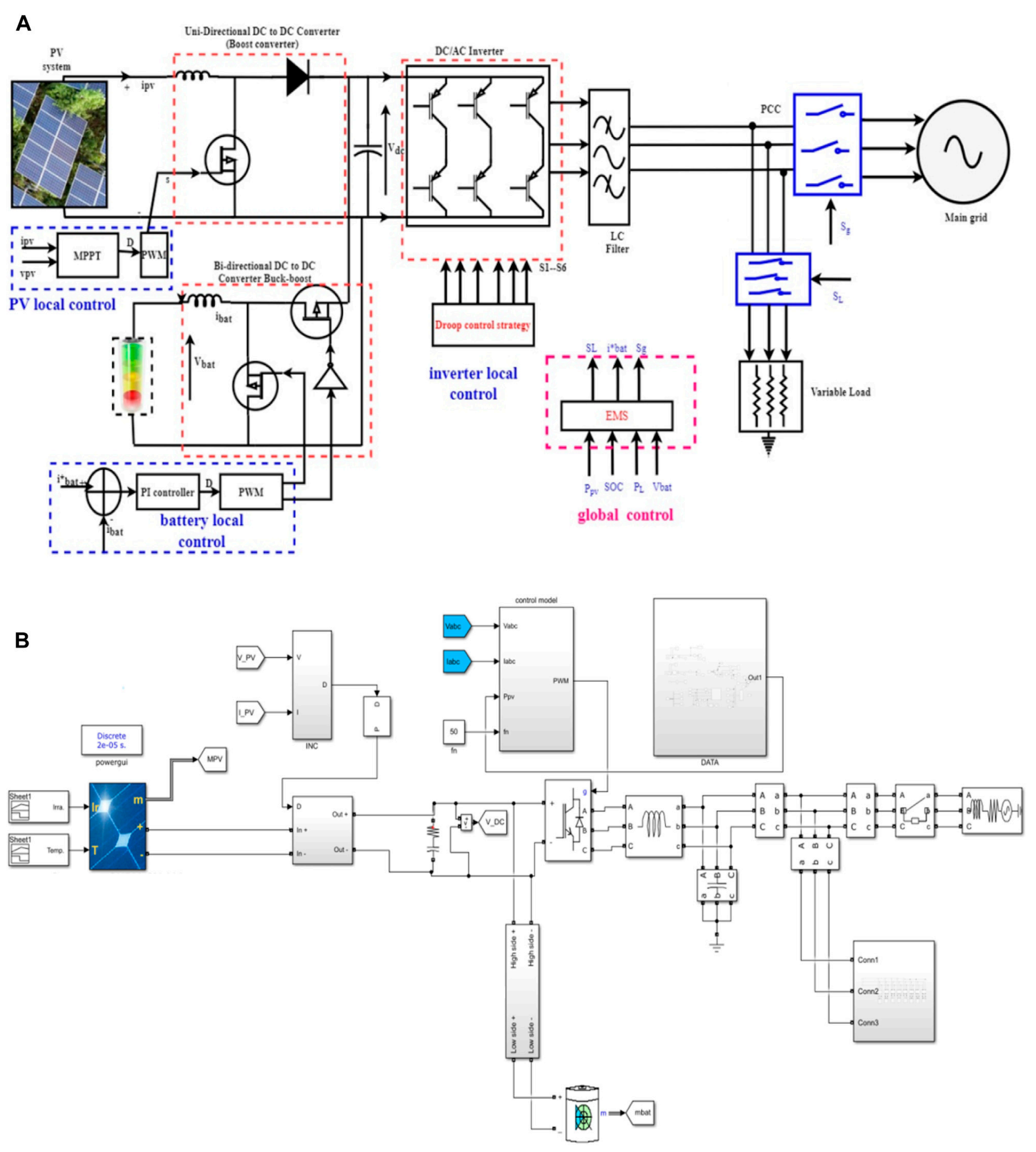

FIGURE 5
(A) The proposed system **(B)**: The proposed system designed by MATLAB software.

Where the frequencies f1 and f2 represent the falling frequencies from points A to B, respectively. P1 and P2 are the ultimate and starting powers, respectively. Figure 3B represents the P-f droops from point A to point B. Based on the negative sign in the formula above; the change in power has an inverse connection with the change in frequency. The correction coefficient, abbreviated as Kf, can also be referred to as a static characteristic coefficient since it reflects the P-F droop's inverse of its sloppy as indicated in Equation 4 (Rezkalla et al., 2018):

$$P_2 - P_1 = \Delta P = K_f \ (f_2 - f_1) \tag{4}$$

It is important to note that while active power-frequency droop control is the main emphasis of this work, reactive power-voltage droop control is also created in this study using the same methodology. Generally, a cumulated control loop system is used to regulate the VSCs at each generating unit. Figure 3 presents a generic non-linear control method for the VSC. The droop

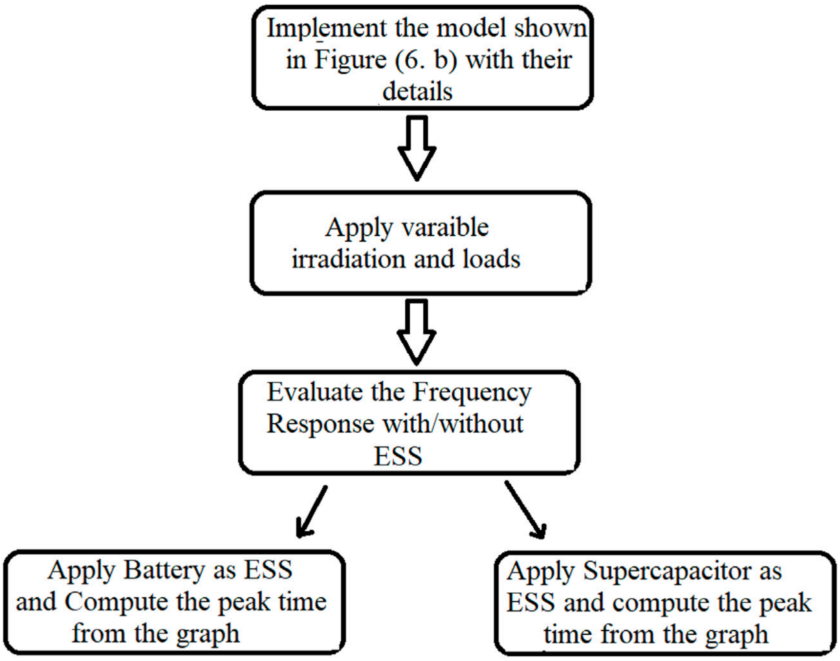

FIGURE 6
The proposed methodology flowchart.

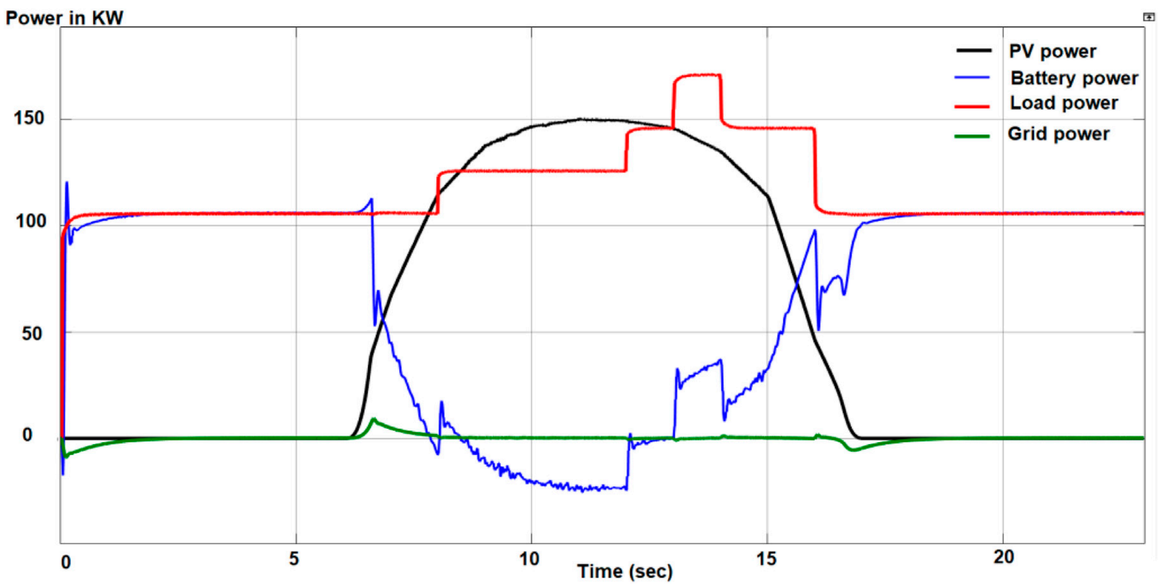

FIGURE 7
The power balance between (PV, Battery, Load and Grid).

controller's goal is to provide the voltage and frequency reference needed for the Voltage and Current Control (VCC) to operate in line with the demands of the power system. Using the Equations 3, 4, the needed power is computed. The voltage and current are regulated and make up the VCC which operates on a dq0 frame. The IGBT (Insulated Gate Bipolar Transistor) of the VSC is driven by the Pulse Width Modulation (PWM) block using space vector modulation SVM. The RES is intended to be a source of steady DC voltage that can provide the required quantity of power (Alghamdi and Cañizares, 2021).

6 Simulation results

Figure 5A depicts the suggested system in this study. It includes a solar PV panel, an B-ESS (or S-ESS), droop control inverter, a

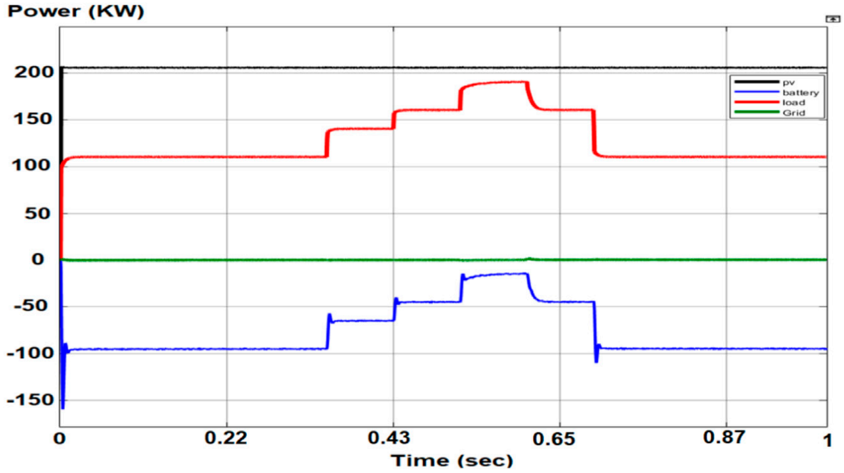

FIGURE 8
The power balance at maximum irradiation.

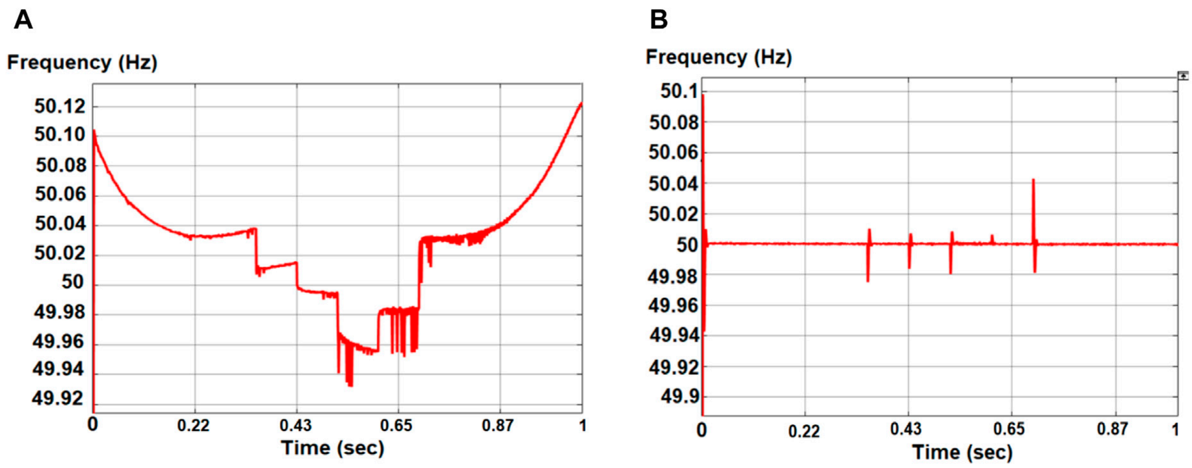

FIGURE 9
(A) the frequency response without battery system, **(B)** the frequency system with battery system.

step-up converter utilized to raise the voltage output of the PV system to DC-bus voltage, the bidirectional converter utilized with a battery system, and the inverter that is managed using a droop technique scheme according to the voltage source inverter control. The proposed system execution by employing the MATLAB software is shown in Figure 5B.

The power balance of the proposed load demand and the PV generation based on the irradiation and temperature of Hail City is shown in Figure 7. The battery is used to supply the required power in case of a shortage in the PV generation system, while the grid is on standby. Another function of the battery system is to supply the system with virtual inertia to reduce the RoCoF and improve the frequency stability.

The PV panel type used in this work is Sunpreme Inc. SNPM-GX-300, which was selected from the MATLAB library with 300 W, 7.8 A, and 38.5 V for each panel. If the selected output power of the PV system is 147.9 kW, then the number of panels can be given by (147.9 kW/300 W = 493 panels) that can be arranged by (17*29) as a farm of panels.

A step-up boost inverter is used to increase the DC output voltage of the PV system to 800 V, and then the inverter is employed here to produce 380 V AC at 50 Hz to comply with the Hail distribution voltage.

The battery system voltage was 400 V, and a bidirectional converter is employed here for the charging and discharging processes. The output DC voltage of the bidirectional converter is also 800 V (identical to the boost output voltage) and is connected in parallel as input to the inverter. The flowchart of the proposed methodology in this work is shown in Figure 6.

The load is variable between 175 kW and 105 kW, as shown in the red line in Figure 7. The irradiation is selected as Hail City's available information.

To explain the frequency response of the proposed system, the time interval of the maximum irradiation (966 W/m^2) at

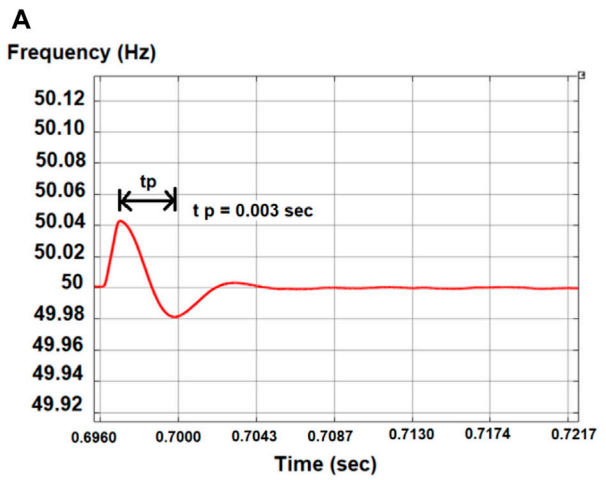

FIGURE 10
(A) the frequency response battery system, **(B)** the frequency system with supercapacitor system.

TABLE 1 Related works comparison.

Ref. No.	Year	Proposed system components	Inverter control	Solutions
Li et al. (2019)	2019	Battery + Inverter + Synchronous generators	Droop	Use battery system
Kpoto et al. (2019)	2019	Battery + Inverter + Synchronous generators + wind turbine	Not classified	Use battery system
Afshar et al. (2020)	2020	Battery + Inverter + Diesel + wind turbine	PQ	Use battery system
Fahad et al. (2020)	2020	PV + Inverter + Synchronous generators + wind turbine	Hierarchical	Improve the inverter control strategy
Celna et al. (2021)	2021	Inverter + Synchronous generators + wind turbine + Supercapacitor	PI	Use supercapacitor system
Pokhriyal et al. (2022)	2022	Inverter + Synchronous generators + wind turbine + battery	Droop control	Use battery system
Nerkar et al. (2023)	2023	PV + Inverter + Synchronous generators + wind turbine	Virtual Inertia Control (VIC)	Improve the inverter control strategy
In this work	PV + + Inverter + Synchronous generators	Droop control	This work shows that the supercapacitor has a high impact on improving the frequency response as compared with battery system	

temperature (15 C°) at 30/Jan/2023 will be taken in the next cases with 210 kW PV input. Figure 8 shows the proposed load demand with the constant PV generation at irradiation 966 W/m^2.

As shown in Figures 7, 8, the MATLAB model of the proposed system examines the EMS and the MPPT of the PV system. According to the proposed droop control of the VSG inverter, which is present in Figure 2.18, the droop control can be explained in the following three stages: The first stage is used to measure the active power and reactive power from the output of the LC filter. The Vd and Vq (direct and quadratic axes) can be calculated at this stage. In the next stage, which is the second one, the comparison between the set values and the measured values (P, Q, V, and F) is implemented as a droop control between them. In the third step of the proposed droop control, the measured Vd and Vq signals are turned into six pulses that are sent to the inverter switch using the PWM method. In cases where there is no ESS (battery system), the frequency response is shown in Figure 9A. The frequency deviation in this case is 0.18 Hz. The frequency above 50 Hz refers to the PV generation being higher than the load demand. The droop control utilized in this work will have a constant frequency of 50 Hz with some oscillations when the load changes. Figure 9B shows the frequency response when the battery system is used.

The next case of this work is to use a supercapacitor instead of a battery; the time response of the supercapacitor is less than that of the battery system. Figures 10A, B show the frequency response when using a battery and a supercapacitor, respectively.

From the power frequency curve shown in Figure 10, we can observe that the straight line of the slope in the frequency in the battery system is greater than in the supercapacitor system, thus meaning the time required to return to the nominal frequency in the battery is greater than as compared with the supercapacitor system.

As compared this work with the previous related work, Table 1 shows briefly a comparison between the system components of each work, inverter control type, and solution to reduce the impact of large-scale penetration of RES on the frequency response (Salah et al., 2017).

7 Conclusion

The additional electricity produced by RES, which has very low inertia, may have a negative impact on the power system's capacity to run continuously and reliably. This paper investigated a number of remedies to the aforementioned issue. The objective of this study is to determine if it is technically feasible to provide an inertial response to electricity grids with significant PV generation penetration using ESS technologies based on batteries. Using the MATLAB/Simulink program, this study suggests batteries to improve frequency stability. The proposed power system inertia was changed by changing the RES penetration level. Whenever the size of the ESS increased and the RoCof decreased, respectively, the results show that, the frequency response can be improved when the battery system is replaced with a supercapacitor system. There are many future ideas or works that the authors have that can be summarized here, such as the use of wind turbines in addition to solar cell systems. Intelligent control methods using artificial intelligence may help improve the frequency and increase its stability. The study of connecting several inverters based on VSG with different sizes to the power grid is also important, as it better simulates reality.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

OK: Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Nomenclature

AC	Alternating Current
CC	Current Control
DC	Direct Current
ESS	Energy Storage System
B-ESS	Battery Energy Storage System
S-ESS	Supercapacitor Energy Storage System
KE	Kinetic Energy
IR	Inertia Response
RES	Renewable Energy Source
IIRES	Inverter-Interfaced Renewable Energy Source
Kd	Damping coefficient
$\mathbf{W_0}$	rated speeds
W	Mechanical speeds
PI	Proportional-Integrator
PV	Photovoltaic
IGBT	Insulated Gate Bipolar Transistor
RoCoF	Rate of Change of Frequency
VC	Voltage Control
VSG	Virtual Synchronous Generator
VSM	Virtual Synchronous Machine
Kf	Correction coefficient
VA	Volt–Ampere
VCC	Voltage and Current Control
PWM	Pulse Width Modulation