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# Evaluating the inertia of the Jordanian power grid☆

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ABSTRACT

The increasing penetration of renewable energy sources in power grids has resulted in the need for a comprehensive evaluation of their impact on the dynamic behavior of the power system, including its inertia. This study aimed to evaluate the inertia of the current Jordanian power system at different penetration levels of renewable energy sources using DIgSILENT PowerFactory simulation software. In this study, the value of the constant inertia was calculated to be 8.755 s. The results were analyzed to determine the effect of renewable energy penetration on the inertia of the power system. The findings provide valuable information for the development of control strategies for integrating renewable energy sources into the Jordanian power system, ensuring stability and reliability in the power system operation. This study contributes to the understanding of the impact of renewable energy sources on power system inertia and supports the development of renewable energy integration strategies.

## 1. Introduction

One global initiative aimed at mitigating the impact of climate change is the shift from fossil fuels to clean energy sources. This has made investing in renewable energy projects more attractive and feasible [1]. While renewable energy sources (RESs) help reduce CO2 emissions and increase energy security, they also bring about more uncertainty and unpredictability to transmission and distribution power grids. The lack of economical energy storage options exacerbates the difficulty in balancing energy generation with real-time demand. Although distributed generation reduces the losses associated with the transportation and transformation of electricity, it also makes the system more complex and requires an efficient management [2]. The rapid growth in electricity demand over the past century has posed a challenge for both energy producers and system operators, and this trend is expected to continue with the electrification of the transportation sector and building heating systems. Traditional power stations are struggling to cope with rising energy consumption, and the current power system infrastructure cannot fully meet the growing demand and complexity brought about by new scenarios in power systems.

Renewable energy in Jordan has great potential, particularly for wind and solar energy. In fact, the annual average daily sunlight in

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Jordan is within the range of 5-7 kilowatt-hours/$m^2$, one of the world's highest figures. In addition, the average wind speed in Jordan is within the range of 7-9 m/s [3].

A significant amount of research has been dedicated to integrating renewable energy sources into remote islands and connecting them with the conventional power grid to create a smart grid scenario [4]. The authors in [1] summarized the latest developments in power converters and provided insight into the grid connection of RES. In addition, many Western and Asian economies have encouraged the development of smart grids because of the policy challenges associated with global warming and the prospect of increasingly expensive fossil fuels [5].

Other researchers have conducted a comprehensive study of a smart grid-connected photovoltaic/wind turbine hybrid system using the MATLAB/Simulink software package. This study aimed to optimize the generated power by employing a maximum power point tracker (MPPT) based on the Perturb and Observe (P&O) algorithm [6], and the dynamic behavior of wind turbine generators (WTGs) should be thoroughly understood. Many studies have analyzed the dynamic models of WTGs and used generic models [7,8].

The integration of renewable energy sources can have significant impacts on the power system, including voltage variations and imbalances, current and voltage harmonics, protection against grid islanding, and other power quality issues, such as flicker and stress on distribution transformers [9,10].

A large penetration of RESs raises several technical issues including low system inertia, low fault ride-through capability, high fault current, low generation reserve, degraded power quality, and a high degree of uncertainty because of their intermittent nature. The work presented in [11] addressed several challenges of high-level RESs (specifically wind and solar) energy integration to the existing grid, as well as cutting-edge technologies as potential solutions, including different control strategies, optimization techniques, energy storage devices, and fault current limiters.

The concept of inertia in the power system refers to the resistance of the grid against frequency changes. In a traditional power system, the stability relies on rotating generation units coupling in the grid where physical inertia is provided. In addition, integrating renewable energy into the power system faces three considerable challenges: reliability, stability, and adequacy. These challenges are considered one of the main drawbacks of integrating many nonsynchronous generators (e.g.: RESs) into the grid. RESs decrease the inertia of the power system affecting the system stability and reliability [12].

The work presented in [13] mainly focused on the low inertia problem of energy conversion systems realized by WTGs. Wind turbine generators are connected to the main grid through power electronics which are electromagnetically disconnected from the rest of the power system, creating low inertia problems for the power system. Several approaches have been used for nonsynchronous RESs to emulate the behavior of synchronous generators and improve the frequency response and stability. This paper reviews the frequency response technologies that exist specifically for wind-power-integrated energy systems. References [14,15], focused on the issue of low inertia in modern power grids owing to the integration of power electronic inverters and renewable energy resources. The high rate of change of frequency (RoCoF) and frequency deviations caused by low inertia affect the frequency stability of the system and present challenges for grid operators. This article provides an overview of the state-of-the-art inertia emulation control techniques for various systems, such as inverters, wind turbines, photovoltaic systems, and microgrids. It also highlights various appropriate technologies for enhancing inertia, and evaluates their strengths, weaknesses, challenges, and additional ancillary services.

Jordan achieved great results in the transition to RESs and looks forward to increasing the share of RESs. The Jordanian power grid (JPG) is facing challenges and new difficulties that may cause a total blackout of the grid. In addition, the COVID19 pandemic has slowed down the economy and affected RESs transition plans [10].

The JPG stability study is crucial because of the enhanced RESs share of 20% of the total generation. This study becomes necessary for the transition to RESs and for the system stability and sustainability under different disturbances: small or large, increase or decrease in the loads, or any other faults in the grid [3].

The objective of this paper is to assess the current level of inertia in the JPG at different levels of renewable energy penetration. It aims to understand the impact of RESs on the frequency stability of the power system.

## 2. Mathematical model

The mathematical model for the inertia of a power system is based on the relationship between the rotational speed of the system and the mechanical power input. The inertia of a power system can be represented by the inertia constant (H), which is a measure of the system ability to resist changes in its rotational speed.

The inertia constant is defined as follows:

$$H = \left( \frac{2*T}{\omega b * \left(\frac{d\omega}{dt}\right)} \right) \tag{1}$$

where T is the kinetic energy stored in the rotors of the generators, ωb is the system base angular frequency, and dω/dt is the rate of change of the system angular frequency (in radians per second).

Equation (1) can be used to calculate the inertia constant (H) of a power system based on the kinetic energy, angular frequency, and rate of change of angular frequency of the system.

The inertia constant can also be determined from the frequency response of the system to a disturbance, such as a step change in the mechanical power input. This can be achieved by analyzing the frequency response of the system and determining its natural frequency and damping coefficient.

The natural frequency and damping coefficient can then be used to calculate the inertia constant of the system using Eq. (2):

$$H = \left( \frac{2 * \omega n}{\left(\frac{d\theta}{dt}\right)} \right) \tag{2}$$

where ωn is the natural frequency of the system, and dθ/dt is the damping coefficient of the system.

It is worth noting that the inertia constant (H) is measured in seconds (s), and it represents how long the system can delay the frequency deviation.

To calculate the inertia constant using the indirect method by simulation, we can set up a disturbance scenario in DIgSILENT PowerFactory, such as a sudden change in the mechanical power input of one of the generators and run the simulation for a sufficient amount of time to allow the system to reach the steady state. The simulation results are stored in the form of time-series data, which can be analyzed to determine the frequency response of the system to the disturbance. The frequency response can be used to calculate the natural frequency and damping coefficient of the system.

The rate at which the frequency of a power system changes is referred to as the Rate of Change of Frequency (RoCoF). In traditional power systems, RoCoF is not a significant concern as the networks do not have significant amounts of RESs or small distributed generators integrated. However, with increasing levels of RESs integration, the RoCoF has become increasingly important for controlling the network frequency. The RoCoF can also be used to detect imbalances between power generation and load consumption, which may be caused by the disconnection of large loads or generators. High RoCoF values can occur when there is low system inertia owing to the integration of a large amount of uncertain generation.

The mathematical model for the RoCoF can be expressed as follows:

$$RoCoF = \left( \frac{d(\Delta f)}{dt} \right) \tag{3}$$

Equations (1)-(3) are integrated in PowerFactory software through a written script using DIgSILENT PowerFactory Language (DPL) to calculate the inertia in a power system that involves multiple parameters, such as the rotational mass, angular velocity, and mechanical power of the generators. The DPL scripts perform the mathematical operations and obtain the required results.

## 3. Methodology

The methodology used in this study was designed to evaluate the impact of the inertia constant and generator rating on the frequency response of the Jordanian power system under different contingencies. To achieve this goal, a simulation model was developed using DIgSILENT PowerFactory, a widely used software for power system analysis and simulation.

The value of the system inertia constant was determined using the DIgSILENT PowerFactory simulation model. Specifically, the power system model was set up and calibrated using data collected from a real power system, which included information on the generator rating.

To determine the value of the system inertia constant, a disturbance was introduced to the system by perturbing the generator speed, and the resulting frequency response was measured using the DIgSILENT PowerFactory simulation model. The natural frequency and damping coefficient of the system were then obtained from the measured frequency response using signal processing techniques within the DIgSILENT PowerFactory software.

The value of the system inertia constant was calculated using the natural frequency and damping coefficient obtained from the frequency response analysis within DIgSILENT PowerFactory. This value was then used in the simulation model to evaluate the frequency response of the system after different contingencies, such as the loss of a generator or a transmission line. In addition, the RoCoF was calculated in this paper using the "RoCoF Protection" function. This function calculates the rate of change of frequency at a particular point in the power system, such as a generator bus, based on the measured frequency values at that point. The RoCoF Protection function uses a time window to calculate the RoCoF, which is typically set to 2-3 seconds.

Overall, the methodology used in this study involved the collection and analysis of data, calibration of the simulation model using DIgSILENT PowerFactory, and analysis of the frequency response after various contingencies using the same software. The results of this study provide valuable insights into the impact of the inertia constant and generator rating on the frequency response, and support efforts towards improving the stability and reliability of the power system in Jordan.

### *3.1. Grid modeling*

The JPG is a three-level system that includes power generation, transmission, and distribution. Power is generated in power plants that use natural gas as a fossil fuel source. This power is then transmitted through high voltage transmission lines to distribution units. Then, power is distributed to end-users through low voltage distribution lines.

The Jordanian electrical power sector consists of three stages: generation, transmission, and distribution. The generation sector, comprising four companies, generates electricity from power plants and provides electricity to the transmission grid. These companies include the Central Electricity Generation Company (CEGCO) with a capacity of 1555 MW, Samra Electricity Power Company (SEPCO) with 888 MW, Qatrana Power Company with a 370 MW combined cycle unit, and Amman East Power Company with a 370 MW combined cycle unit. The transmission sector, managed by the National Electric Company (NEPCO), includes two high voltage transmission lines (132 and 400 kV). Finally, three companies –Jordan Electric Power Company (JEPCO), Irbid District Distribution Company (IDECO), and Electricity Distribution Company (EDCO) – are responsible for distributing electricity at low voltage in different areas of Jordan.

Most renewable energy projects, consisting mainly of wind and solar generation, are located in the southern part of the country, and have a total capacity of approximately 995 MW, connected to the southern part of the National Grid, the Aqaba generation and the Egypt-Jordan connection line.

The entire JPG was simulated using DIgSILENT software to include all 132 kV and 400 kV transmission lines, generators, and substations. Fig. 1 depicts a geographic single line diagram (SLD) of the national grid, modeled using DIgSILENT PowerFactory, with red lines representing 400 kV transmission lines and green lines representing 132 kV transmission lines.

The real JPG is used in this study to highlight the effects of the inertia constant and the generator rating MVA on the frequency response after contingencies.

In this study, two power plants were connected to 400 kV transmission lines, and another two power plants were connected to 132kV transmission lines. Fig. 2 shows the SLD for two power plants modeled in DIgSILENT PowerFactory software that are connected to 400 kV transmission lines. As shown in Fig. 2a, the SAMRA power plant consists of six generators with a total of up to 130 MW each, and six transformers, one for each generator. Fig. 2b presents the Amman East power plant SLD, which consists of three main generators with 120 MW each, and 19 diesel generators with 14.5 MW each used as backup.

Figure 3 shows the SLD of two power plants modeled in DIgSILENT PowerFactory software that are connected to 132 kV transmission lines. As shown in Fig. 3a, the ACWA power plant consists of three generators that total up to 130 MW each, and one generator with a transformer for each generator. Fig. 3b presents the SAMRA power SLD, which consists of three generators with 130 MW each and 19 diesel generators with 14.5 MW each used as backup.

## 4. Results and discussions

This study considered different scenarios to evaluate the inertia of the current JPG without renewable energy, and with different penetration levels of RESs.

### *4.1. Scenario 1*

The first scenario analyzed the power flow for four power plants, two of them connected to 400 kV transmission lines, and the remaining two connected to 132 kV transmission lines. The objective of this scenario was to determine the baseline data for all power plants.

In this scenario, all the energy generated is used as during normal operation with a peak load, without renewable energy generation. The results show that the generators in both the power plants selected maintained a frequency of 50 Hz at all locations on the grid, as shown in Figs. 4a and b.

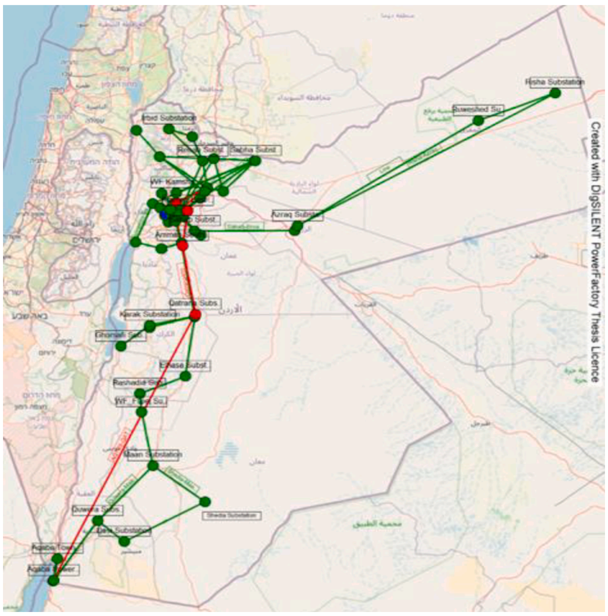
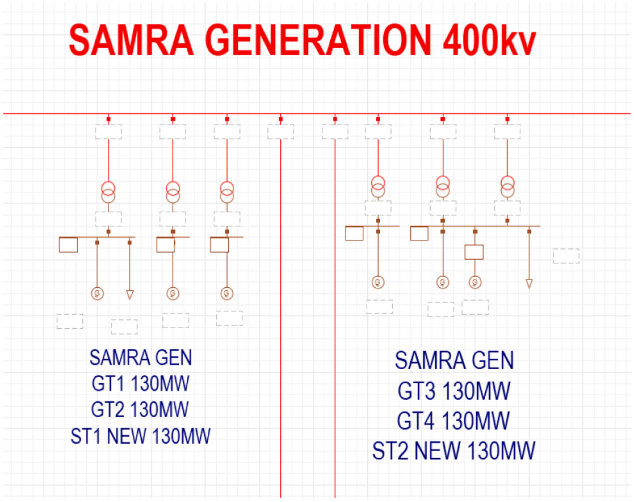
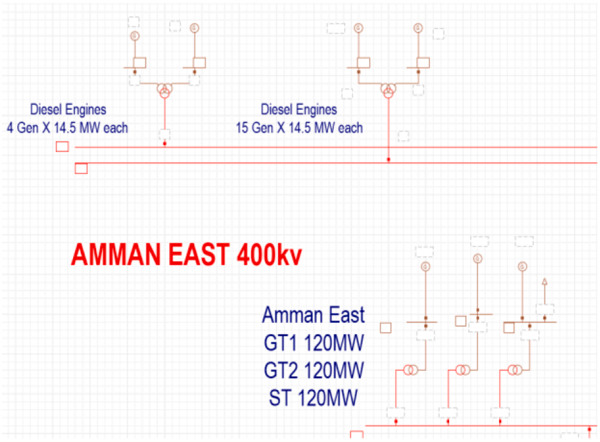



**Fig. 1.** Geographic SLD of the Jordanian national grid using DIgSILENT software




(a)




(b)

**Fig. 2.** (a) SAMRA power plant single line diagram, (b) AMMAN EAST power plant single line diagram

Figure 5 presents a time series analysis of the power output from different generators with varying capacities over a 60-second time period. The generators are labeled according to the name of the power plant to which they belong, including six generators in the SAMRA power plant and three generators in the Amman East power plant connected to 400 kV transmission lines. Each generator is represented by a color-coded line on the graph.

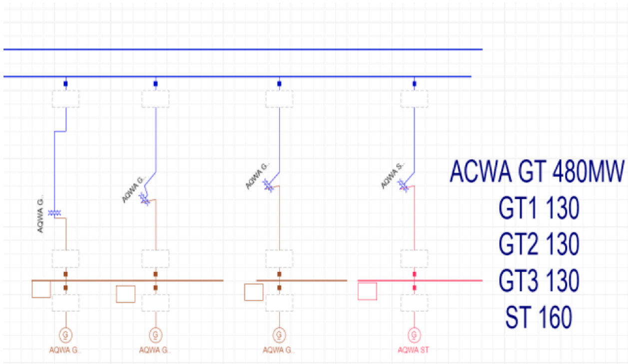
In the SAMRA power plant, each of the six generators has a rated capacity of 130 MW. As shown in Fig. 5, not all generators are operated at full capacity during the time period analyzed. Only three of the generators operate at full capacity, while one generator maintains a steady output of approximately 100 MW, and the steam generators operate at 50 MW. The graph reveals fluctuations in the power output over time for the SAMRA power plant generators, indicating variations in performance and efficiency.

Figure 5 also displays the results for the three generators at the Amman East power plant, which maintain a relatively steady output of approximately 120 MW each, with minor fluctuations observed at the beginning of the simulation. These fluctuations can be due to changes in demand or other external factors affecting the generator performance.

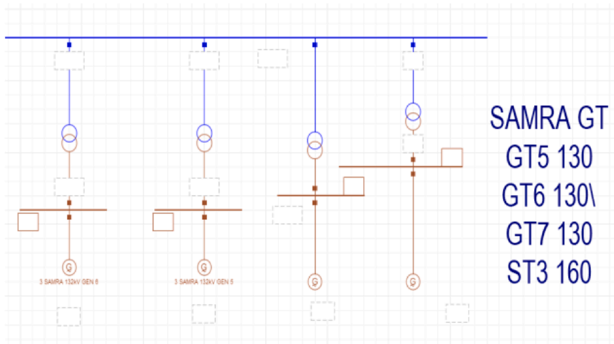
The time series analysis of the power output provides valuable insights into the performance and efficiency of different generators operating under high load demand, which measured approximately 2800 MW.

A time series examination of the power output from various generators with variable capacities over a 60-second period is shown in Fig. 6. Four generators are located in the SAMRA power plant, and four generators are located in the ACWA power plant, both of which are connected to 132 kV transmission lines. The generators are identified by the name of the power plant to which they belong. In the graph, a line with a corresponding color designates each generator.

The results show that all generators are operated at full capacity during the time period analyzed. Only two of the generators




(a)




(b)

**Fig. 3.** (a) ACWA power plant single line diagram, (b) SAMRA power plant single line diagram

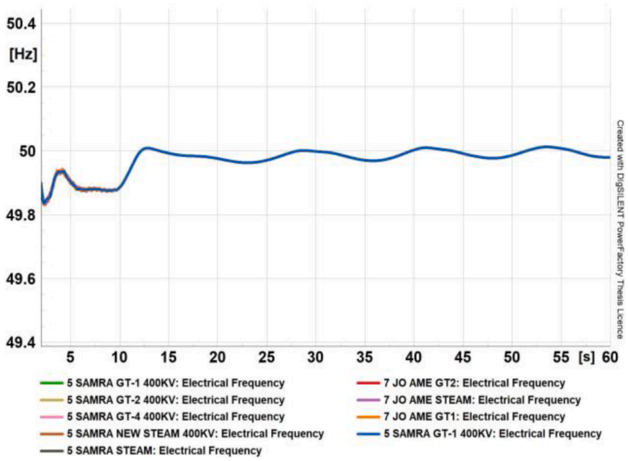



**Fig. 4a.** Frequency for the generators connected to 400 kV transmission lines.

operate at 50 MW capacity, while one generator maintains a steady output of approximately 100 MW, and the rest of the generators operate at a capacity of approximately 130 MW.

### *4.2. Scenario 2*

This scenario aims to investigate the impact of power grid inertia during contingency events on the stability of the power system and proposes measures to improve the resilience of the system in similar situations. However, the inertia of the power grid is examined at contingencies with peak load demand and without renewable energy generation.

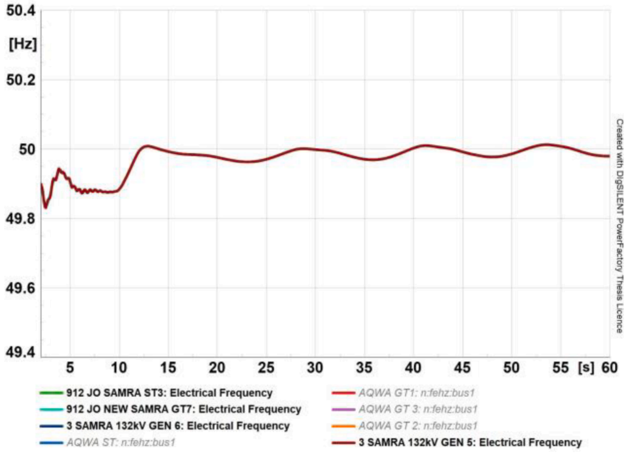



**Fig. 4b.** Frequency for the generators connected to 132 kV transmission lines.

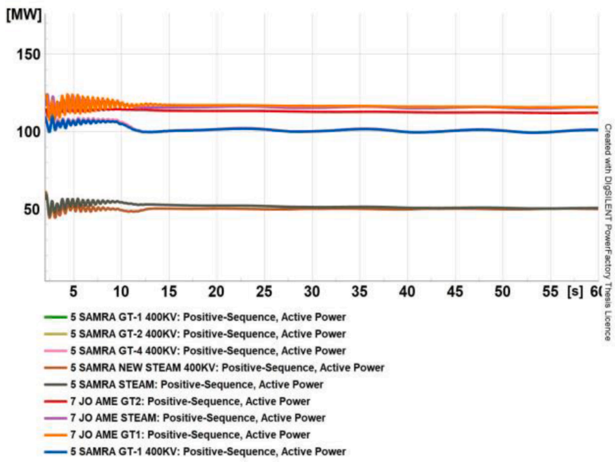



**Fig. 5.** Power for the generators connected to 400 kV transmission lines.

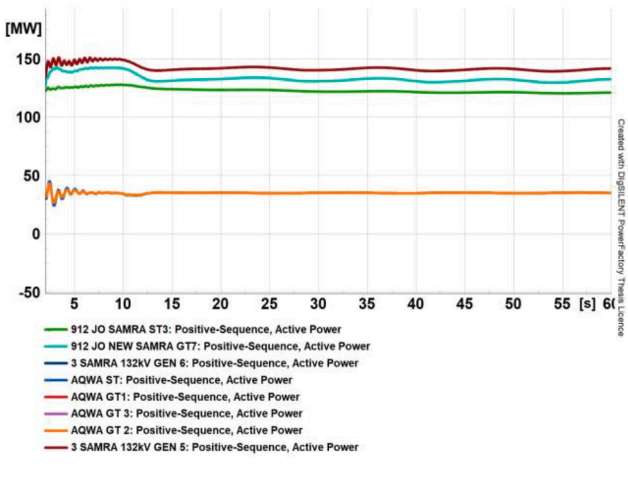



**Fig. 6.** Power for the generators connected to 132 kV transmission lines.

The SAMRA power plant has three generators with a total capacity of 390 MW, constituting approximately 17.8% of the overall power generation in the system. According to Table 1, these generators disconnected from the network after four seconds, whereas the remaining generators continued to operate. Fig. 7 illustrates that the frequency was unstable before the generators tripped, owing to the mismatch between generation and demand. Specifically, when the demand exceeded the rated generation, the frequency dropped. Following the contingency, the frequency dropped to 49.56 Hz, resulting in a significant change in RoCoF of 0.48 Hz/s.

The results show that all generators connected to both the 400 kV and 132 kV transmission lines operated at their maximum power capacity to maintain grid stability. Minor fluctuations were observed at the beginning of the simulation, as illustrated in Fig. 8.

In this scenario, the constant inertia of the power grid was 8.755 s, indicating a sufficient level of stability and resilience. The system demonstrated no instances of collapse or blackout, suggesting that effective measures are in place to maintain the stability of power grid in the face of potential contingencies.

### *4.3. Scenario 3*

This scenario is similar to Scenario 2, being the disconnection of an additional 390 MW generator at the 132 kV level the only difference. The primary aim of Scenario 3 is to replicate a historical blackout incident that occurred in the Jordanian power grid. This scenario involves disconnecting two generators at the 132 kV level, resulting in a total loss of generation capacity of 780 MW, equivalent to approximately 35.4% of the overall power generation in the system, similar to the historical blackout incident caused by a system failure.

In this scenario, all six generators were disconnected from the rest of the grid after five seconds. Similar to Scenario 2, Fig. 10 displays a decline in frequency to 48.8 Hz due to an imbalance between power generation and demand. The system attempted to stabilize the frequency through a secondary frequency response, but immediately after the contingency event, the rate of change of frequency (RoCoF) experienced an exceptional alteration of 1.210 Hz/s. This occurred because of the limited MVA rating of the small generators and high load demand, resulting in a deficit of active power (MW) in the system. The frequency instability was caused by an imbalance between the amount of power generated and the load demand, leading to a decline in frequency whenever the demand exceeded the rated generation. After the contingency, the frequency dropped to 48.8 Hz, causing a significant RoCoF change of 1.2 Hz/s. Fig. 9 depicts that the system eventually collapsed after approximately 50 seconds due to the lack of active power in the grid. The root cause of this blackout, as indicated in the scenario, was an imbalance between power generation and demand, and the secondary control action was insufficient to generate enough power to stabilize the frequency and prevent the system from collapsing.

When 35.4% of the total generation capacity is missing, the system faces low inertia, which causes a blackout according to this scenario.

### *4.4. Scenario 4*

This study examines different scenarios to evaluate the inertia of the grid under current conditions, with a particular focus on the installed renewable energy sources. Most renewable energy in this context is comprised of wind and solar generation, located predominantly in the southern region of the country, and possesses a combined capacity of approximately 995 MW. These RESs are integrated into the southern portion of the Jordanian grid. The specific cases considered in this scenario are presented in Table 2, where all the previous scenarios with renewable energy to study their impact on inertia and power system stability are also included.

In Case 1, all the energy generated is used as in normal operation with peak load and renewable energy generation. Fig. 10 shows the power plant generation for this case with 2,227 MW capacity, equivalent to approximately 68% of the overall power generation in the system. As it can be seen, the grid is powered by renewable energy, with a peak generation of around 995 MW, equivalent to approximately 32% of the overall power generation in the system.

Additionally, the findings indicate that the frequency profile remained stable at 50 Hz across all locations on the grid, as demonstrated in Fig. 11.

RESs, such as wind and solar power, typically have low inertia compared to traditional power plants, which can make it more challenging to maintain system stability and frequency control. This is because renewable energy sources typically use power electronics to convert the DC output of wind turbines or solar panels into AC power, which can be fed into the grid. Power electronics typically have low inertia, which means that they are less effective in responding to changes in the system conditions and maintaining a stable grid frequency. However, the results in Case 2 show that the renewable energy generation improves grid inertia at a high load demand, resulting in a significant change in RoCoF of 0.35 Hz/s. In addition, the constant inertia of the power grid in this case was 5.874 s, which is better than in Scenario 2.as shown in Fig. 12.

In Case 3, a situation of low demand and high renewable energy output was examined, similarly to that observed during the COVID-19 pandemic in 2020. In some instances, during this period, the renewable energy output exceeded the demand for electricity, resulting in an excess of generation in the system. This surplus generation can cause the frequency to rise, potentially leading to

**Table 1**
Generator operation at scenario 2

| Generator name | SAMRA GT-3 (400kV) | SAMRA GT-4 (400kV) | SAMRA STEAM (400kV) |
|---|---|---|---|
| Capacity (MW) | 130 | 130 | 130 |
| Status | Off | Off | Off |

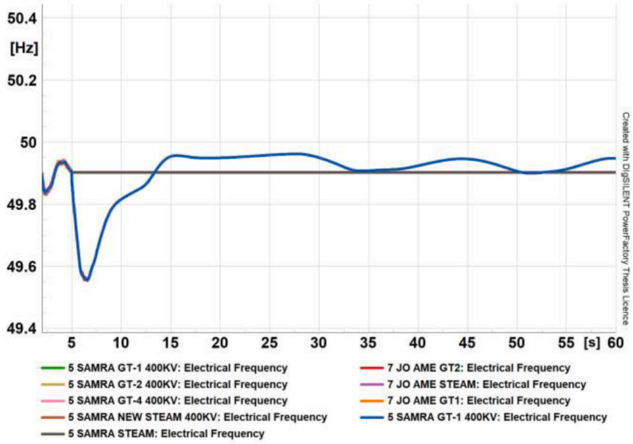
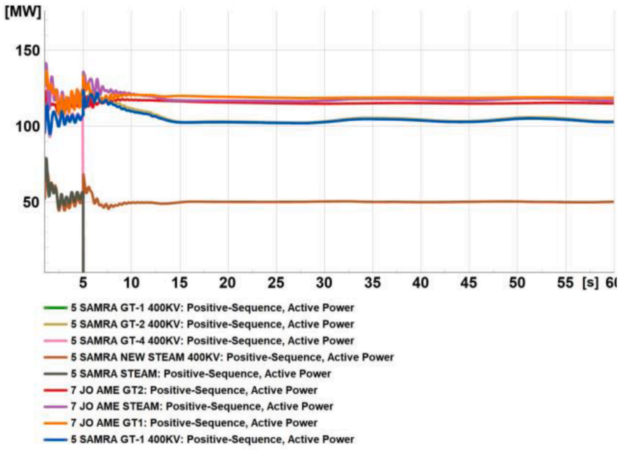



**Fig. 7.** Frequency for the generators connected to 400 kV transmission lines (Scenario two).




(a)


(b)

**Fig. 8.** Power for the generators connected to (a) 400 kV transmission lines and (b) 132 kV transmission lines.

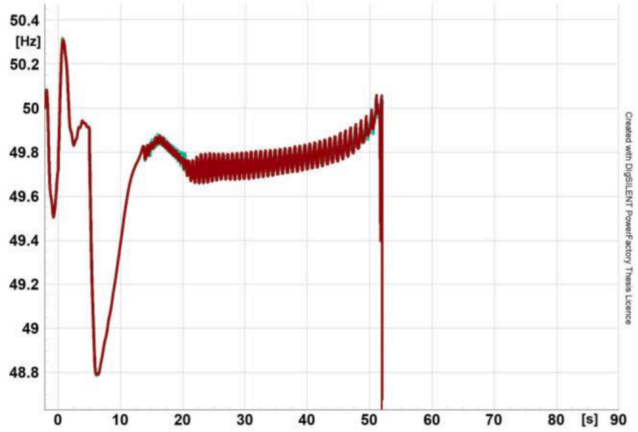



**Fig. 9.** Overall system Frequency (Hz) in Scenario 3.

**Table 2**
The case study scenario

| Case No | Scenario | Renewable energy penetration | Load Demand |
|---|---|---|---|
| 1 | Scenario 1 | High | High |
| 2 | Scenario 2 | High | High |
| 3 | Scenario 2 | High | Low (50%) |

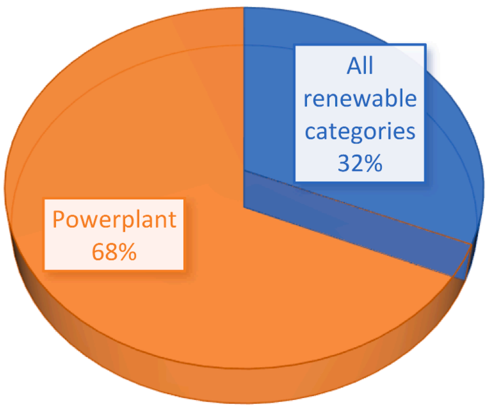



**Fig. 10.** Power plant and Renewable power generation

instability and blackouts if there are not sufficient system resources available to balance the excess generation.

For Case 3, a typical day with a peak demand of 3 GW and a minimum demand of 1.5 GW was considered. At 6 s, the demand for electricity dropped to 1.5 GW, which is approximately 50% of the total demand, whereas the renewable energy output reached its peak of 995 MW. In this scenario, the total generation on the system would be 2.4 GW, with 995 MW from renewable sources and the rest from conventional power plants. As shown in Fig. 13, the system loses stability, and the frequency increases above the acceptable range of 49.5–50.5 Hz, which leads to system instability and a blackout after 48 s.

Based on our analysis, the results demonstrate that the RESs currently installed in the Jordanian grid are not sufficient to improve the grid inertia during a contingency event. This underscores the need to carefully manage the balance between generation and demand on the grid, particularly during situations of low demand and high renewable energy output.

To achieve this, measures, such as curtailment of renewable energy, ramping up other generation resources, implementing demand response programs, and investing in energy storage systems, can be employed. These measures will help maintain a stable and reliable power system operation, ensuring that frequency deviations are detected and addressed before they lead to system instability or blackouts.

Therefore, it is important for power system operators in Jordan, and other countries that face similar challenges, to invest in flexible power generation resources and energy storage systems to ensure a sustainable and resilient energy future. In addition, advanced control systems and monitoring tools should be utilized to detect and address potential frequency deviations in a timely manner. By

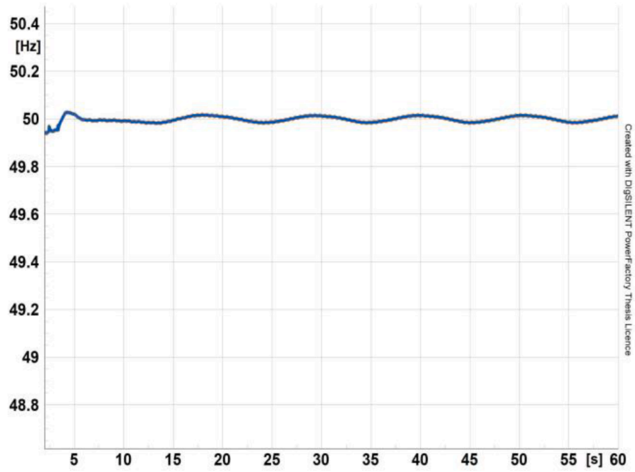



**Fig. 11.** Overall system frequency profile at Case 1

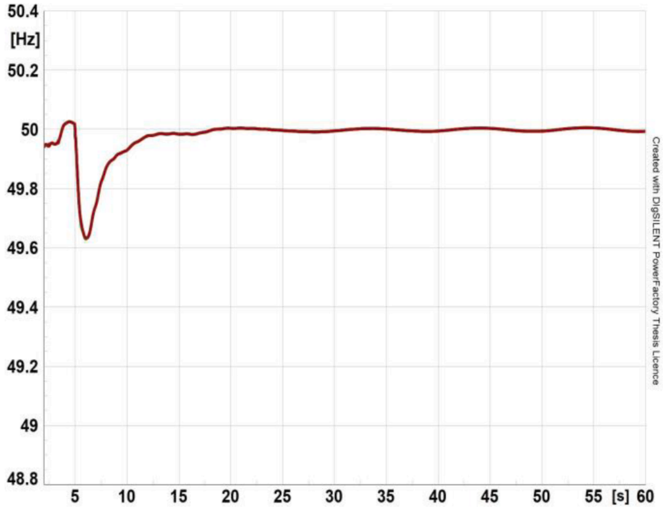



**Fig. 12.** Overall system frequency profile at case 2

taking these steps, it can be ensured that renewable energy integration contributes to a stable and reliable power system operation.

## 5. Conclusions

This study conducted a comprehensive evaluation of the impact of renewable energy penetration on the inertia of the Jordanian power grid using DIgSILENT PowerFactory simulation software. Different scenarios were considered, including the current Jordanian power grid system's inertia without renewable energy and varying penetration levels of RESs. The constant inertia of the power grid was calculated at 8.755 s, indicating a sufficient level of stability and resilience. However, when different penetration levels of renewable energy sources were introduced, the inertia of the power grid decreased. When 35.4% of the total generation capacity was missing, the system faced low inertia, leading to a blackout, according to Scenario 3. This study emphasizes the importance of managing the generation and demand balance during periods of low demand and high renewable energy output in order to maintain a stable power system. Investment in energy storage systems and flexible power generation resources is crucial for a sustainable and resilient energy future. The future work of this study will consist of evaluating the necessary measures to address the challenges posed by the integration of renewable energy.

## Declaration of Competing Interest

None

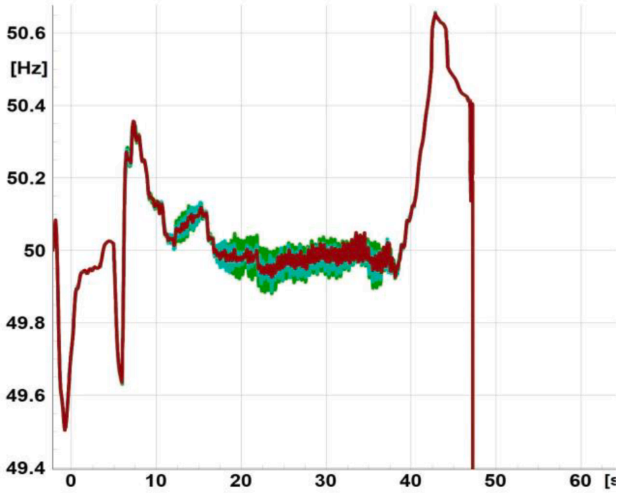



**Fig. 13.** Overall system frequency profile at case 3

## Data Availability

Data will be made available on request.

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