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The Impact of Renewable Energy on the Stability of Future Power Systems

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Abstract. Green energy policies are accelerating the integration of renewable energy sources (RES) across Europe. The transition significantly reduces the share of conventional synchronous generation, which historically ensured power system stability through inertia. This paper investigates the implications of reduced inertia in two European high-voltage grids: Eastern Germany's 50Hertz network and the Balearic Islands' grid. Simulations performed using DIgSILENT PowerFactory v2024 analyse static and dynamic stability under current and future scenarios. Results indicate critical voltage and frequency deviations under high-RES penetration, underscoring the necessity of adaptive stability measures. The findings guide strategies for maintaining reliable electricity supply amid evolving generation portfolios.

Key words. Renewable energy sources, DIgSILENT PowerFactory, stability analysis, 50Hertz, Balearic Islands

1. Introduction

A general characteristic of electricity systems is power balance, i.e., the amount of power produced and consumed on the system is always the same. This is because electricity cannot be stored in the form of alternating current, therefore, generation needs to be continuously adjusted to consumption. A characteristic property of AC transmission is the frequency, which is the same at all points of the system during normal operation and is a prerequisite for a safe and efficient supply. [1]
In conventional electricity generation, energy is produced by synchronous generators, otherwise known as rotating machines. These machines are characterised by their nominal rotational speed, which ensures a constant frequency on the system. The rate of change of frequency (ROCOF) value is a df/dt derivative, and in the case of a system consisting of multiple synchronous generators, can be described as:

$$\frac{df}{dt} = (P_M - P_G)\frac{f}{2HS}[Hz/s] \tag{1}$$

where: PM is the sum of mechanical power of all machines in the system [W],
PG is the sum of maximum electrical power of all machines [W],
H is the system inertia constant [s],
S is the nominal power [W].

In solar PV and wind based renewable energy production, power plants are connected to the grid not by rotating machines but by power electronics. These devices are made up of electronic components, and do not contain any rotating mass. Their proliferation reduces the rotating mass and the kinetic energy it represents on the networks. This reduction in inertia means that the system is less able to damp power imbalances. The higher the share of renewable generation, the higher the inertia loss will be, so RoCoF values will be higher on the grid. [3]

This issue can pose challenges for the stability of power systems, as inertia on European networks has been decreasing in recent years due to the transformation of the power plant portfolio. Green energy solutions in Europe are increasing the use of weather-dependent renewable energy sources. The national climate strategies of the EU Member States define the share of renewables to be implemented on the grids, which can be used to infer the reduction of the rotating mass in each country. In this study, areas where significant inertia reductions have occurred or will occur in the near future are examined. In particular, two of these grids where there are significant differences in terms of the physical extent of the transmission network, system load, and interconnections with neighbouring networks, are discussed, one of them being the power system of Eastern Germany, the other of the Balearic Islands of Spain.

2. Description of grids and the modelling environment

DIgSILENT PowerFactory v2024 was utilized for modeling and simulation. The tool supports load flow analysis, dynamic stability, and custom scripting. Networks were modeled with detailed parameters, including generators, transformers, and renewable sources. Scenarios represent current conditions and projections for 2030, aligning with regional energy strategies.

The networks studied include:

- 50Hertz Network (Eastern Germany): Characterized by high renewable integration (72% in 2023) and significant cross-border connections. The network includes 380 kV and 220 kV transmission levels with substantial wind and solar capacity. The geographic attributes of this landmass make it ideal for wind generation, as in 2023, 32% of total capacity came from wind farms. Solar PV and wind capacities amounted to 43,575 MWp, 62% of the total capacity. [4] Weather-dependent renewable energy generation is already predominant in the generation portfolio.

With a daily maximal system load of 13,000-16,000 MW, it belongs to the bigger grids within Europe. [4] In the aspect of cross-border capacities, it is connected to the neighbouring TenneT Germany, as well as the Czech, Polish and Danish TSOs, providing many opportunities for both import and export.

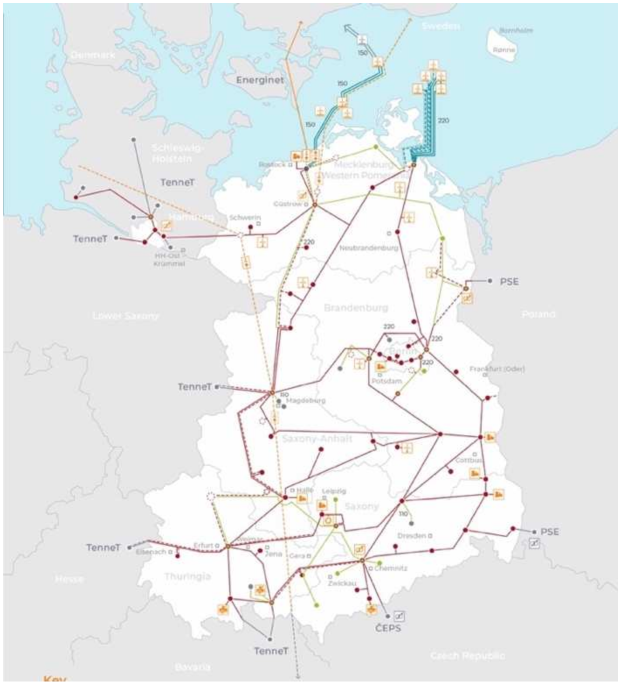

Fig.1. Static grid topology of 50Hertz [5]

During the modelling procedure, the static grid model data available on the 50Hertz website was used, where network elements, such as transformers, lines and cross-border capacities can be found in a table. [5]

- Balearic Islands grid: A smaller, semi-isolated system with a 250 kV HVDC connection to mainland Spain. 4 islands of the archipelago are interconnected via high-voltage cables. The system also displays a partially radial structure, meaning the smaller islands cannot directly support each other with imported power, and the system is located on the grid-edge of the continental network, with few opportunities for cross-border trade.

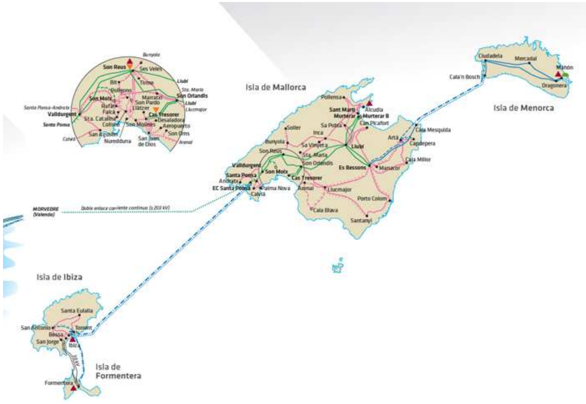

Fig.2. Transmission system of the Balearic Islands [12]

The stability of the islands' network is ensured by 5 thermal power plants with a combined installed capacity of around 1600 MW. [14] In addition, in 2023, 337 MWp of solar power plants were operating on the island, which is about one fifth of the thermal capacity. [15] The energy targets set for the Balearic Islands for climate protection are very ambitious. By 2030, 35% of the energy consumed should be produced from renewable sources, and by 2050, 100%, of which 70% should be produced locally. [16] Thus, a large increase in renewable capacity is expected in the future, leading to a reduction in inertia.

For the modelling, there was no official static grid data available, therefore, a grid report, maps, and models available in the DIgSILENT Library were used.

3. Load flow simulations and results

Several simulation methods are available to provide a complex overview of the conditions in power systems. In static simulations, the network elements have constant characteristics. An environment in which the elements operate at a given value is created, as if one was to take a snapshot of the grid's operation. Within this framework, load flow simulation shows how the power characteristics of each element evolve on the way from generators to consumers, under static power conditions for both. In this case, PowerFactory assumes a steady state with the whole system operating at the nominal frequency (50 Hz for both networks). Thus, this simulation is not suitable to investigate the ROCOF values, but the voltage response provides valuable information on the network stability.

To run the load flow for both networks, the midday hours of a summer day were chosen to reflect the effect of solar PV generation in the results. For the Balearic Islands, this is the time of the annual peak in system load, which was 950.5 MW at the selected time, with 18.6% of generation coming from local renewables. During the load flow simulation, it was observed that all busbars on the islands were operating at less than nominal voltages of 0.95-0.98 V.E. In the 2030 configuration at least 35% of the generation is from renewables. [16] Accordingly, the more expensive OCGT plants were decommissioned in the model and the shortfall was covered by increasing renewable capacity. According to the energy strategy, electricity consumption is expected to increase, so the load flow was run for both 10 and 25% increases in consumption. A power plant portfolio with 50% load increase was also created, however in this configuration the load flow could not run. As a comparison, the load flow was also run with data of early morning hours on a winter day when the solar plants were not generating, the generation came from the thermal plants and the continental system, and the dawn hours resulted in a much lower system load of about 45% of the summer daytime value. The results of the simulations are plotted in a magnitude-phase angle diagram in Fig.3.

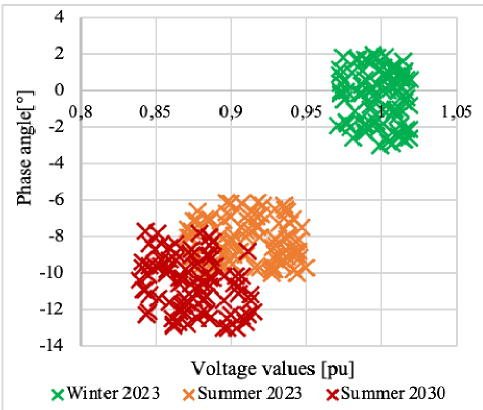

Fig.3. Voltage values on the 50Hertz grid

For the current network state of 50Hertz, both a recent summer and winter day's data were used. The summer day was the day with the lowest system load of the year and at this time of the day PV generation peaked at 10,059 MW. The instantaneous total system load was 8443 MW. This was compared to the annual peak system load, with data from the evening hours of a winter day when the load was 16,462 MW, almost double the summer value.
In the summer scenario, 67.27% of the generation came from renewable sources, and 39.68% in winter. Overall, in 2023, 72% of the electricity generated in the 50Hertz area came from renewable energy sources, which is very close to the 80% target set for 2030. [4] Thus, the 2030 configuration required far fewer changes to the power plant portfolio than the Balearic Islands. The resulting voltage values are also plotted here in a magnitude-phase angle diagram in Fig.4.

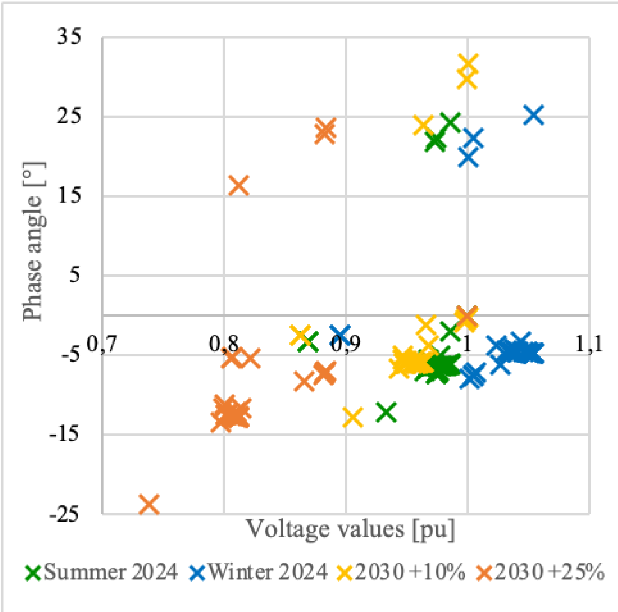

Fig.4. Voltage values on the Balearic system

In the case of the Balearic Islands, as shown in Fig.3, the bars were at or above nominal voltage in the winter scenario, while in all three other cases they were mostly below nominal. As the system load value increased, the average voltage magnitude decreased, confirming our expectations based on theoretical knowledge.

For 50Hertz, the voltage values in both summer scenarios were close to each other, but visibly decreased for the higher renewable fraction. This suggests that the reduction in consumption alone will not lead to a large voltage drop, however, if the aim is to reduce conventional generation on the grid beyond the 2030 target, further voltage drops could occur.
By comparing the voltage values experienced on the two networks, it can be stated that 50Hertz is more stable. This is not necessarily due to the multi-looped structure of the network. It was interesting to see that the large network with the looped structure produced much more consistent values than the smaller network, which was less sub-looped and resembled a radial network in many places. This leads us to conclude that for regions such as the Balearic Islands, the role of network extension will be important to maintain stability alongside the changing power plant portfolio.

4. Dynamic simulations and results

In real systems, consumption and correspondingly generation are constantly changing, and the resulting total load affects the behaviour of the system and its characteristics in different ways. To showcase this phenomenon, transient simulations were performed using PowerFactory's RMS, or electromagnetic transient based simulation function.
Dynamic simulations require the use of control tools. These are the functions that, by giving feedback on the state of the system, influence the generation to balance it with the consumption, and to improve the quality of service. In this study, primary control was used, which aims to keep the system frequency at the nominal value and to minimise the magnitude and duration of deviations from it. A structure of control devices was assigned to each synchronous generator, which consists of a turbine controller, an excitation controller, and a swing controller. These were implemented using the TGOV1, SEXS and PSSA2 control models, which are available in the DIgSILENT Library.

For the dynamic simulations, real system data was used. For both networks, from 2 different days was chosen, which were different both in terms of season and business day/weekend, as these factors have a significant impact on the system load. For 50Hertz, these days are the maximum and minimum system load days for the year 2023. [4]
The exact production data for 50Hertz were developed using source [20]. After running the simulations, the frequency values of a busbar in the systems from PowerFactory was retrieved. Since frequency is a global characteristic of power systems, one can assume that the exact busbar is irrelevant for the results.

For the configuration of a future system, system load was reduced by 20% and renewable share was increased to 80% on average, similar to the static simulations. From the frequency values obtained in the three simulations, ROCOF values were calculated and plotted on a separate graph.

It is important to note that the time step for the time series data was always 15 minutes, so these are not instantaneous ROCOF values. In the case if using higher resolution time series data, the resulting ROCOF values will also approximate the instantaneous value, but these results are illustrative of approximate expected instantaneous values.

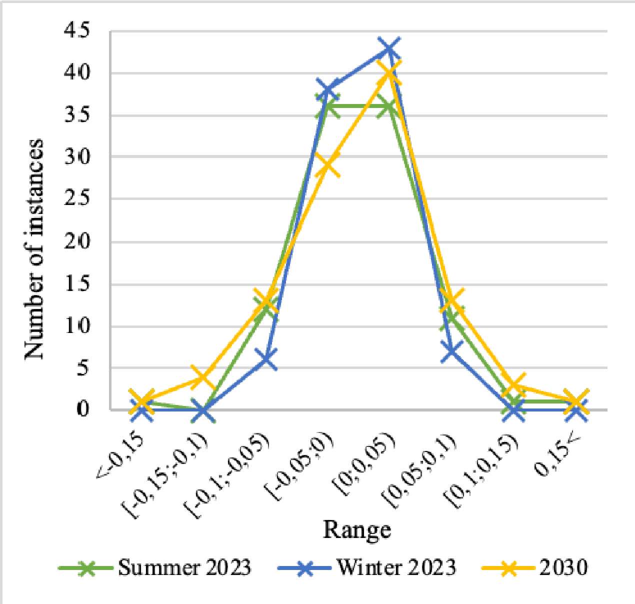

Fig.5. Distribution of ROCOF values on the 50Hertz grid

For the Balearic Islands, system load data was used of the same days used in the load flow simulations. For the two networks, the annual peak and minimum nadir are exactly the opposite. While the peak in Eastern Germany is in the winter, the peak on the islands is in the summer, a difference due to climate and economic conditions.
For the production and consumption data series for the islands, source [15] was used. For the future configuration, the load was increased by 25% and the OCGT plants were put out of operation, just as in the static simulations.

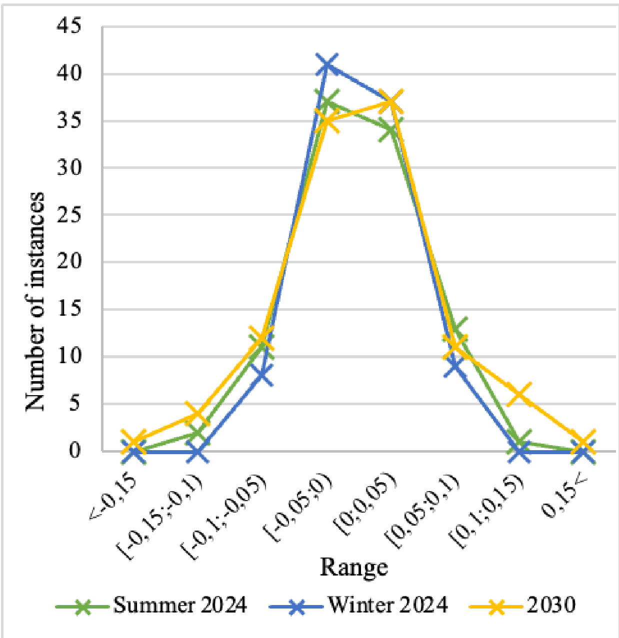

Fig.6. Distribution of ROCOF values on the Balearic Islands grid

The results show that higher system loads and higher renewable penetration increase the ROCOF absolute values, but not to a large extent compared to states with lower system loads and low renewable penetration. This demonstrates that the primary control worked well and that the residual inertia on the system was able to dampen the frequency deviations. In none of the cases was the simulation unable to run due to frequency fluctuations.

The 50Hertz frequency diagram shows that despite the reduction in consumption, high renewable share has a negative impact on frequency fluctuations. In the 2030 configuration, we observed both high and low frequency excursions, with a minimum of 49.788 Hz and a maximum of 50.135 Hz. In terms of ROCOF values, the high spikes were measured between 16:30 and 20:00, the peak period of the daily system load, when, during the summer, photovoltaic generation is still present on the system. These characteristics put stability at greater risk during this period than the rest of the day.

In the Balearic Islands, frequency fluctuations have increased during the summer, with higher system load days and an increase in renewable generation. Here, the minimum and maximum values were less extreme than those on 50Hertz, 49.8705 Hz and 50.119 Hz respectively. However, the ROCOF diagram showed larger deviations from 0 than for 50Hertz. Extreme ROCOF values appeared several times during the day in the 2030 configuration. During the day, the morning and evening peak and the times of maximum photovoltaic production around noon showed outstanding ROCOF in absolute value. This indicates that the control was less effective than at 50Hertz. Frequency stabilization solutions may be needed in the future to achieve higher system loads and renewable penetration than investigated in this study.

5. Conclusion

The two networks have been affected differently by changes in consumption and the spread of renewable energy production. Even though the grid of 50Hertz has more factors contributing to stability, the frequency showed greater extremes for this network. For ROCOF, however, the primary control was more effective, in most cases it could remain lower than in the Balearic Islands. In terms of voltage deviances, 50Hertz again proved to be more stable.

In grid-edge regions, an increase in consumption can result in a large voltage drop, leading to a deterioration in power quality. A high share of renewable generation will result in a reduction of the effect of the primary regulation of synchronous machines, with the possibility of higher frequency deviations from nominal output and higher ROCOF values for longer periods. This may also be the case for large networks in the interior of the continent, but to a lesser extent.
The comparative analysis highlights that smaller, isolated grids are more vulnerable to stability challenges than large interconnected systems. However, both require adaptive control strategies and infrastructure upgrades to accommodate high-RES penetration. Recommendations include deploying grid-forming inverters and expanding energy storage capabilities.

6. Summary and outlook

This study underscores the criticality of addressing stability challenges posed by renewable energy integration. Large-scale inertia losses can affect power quality in a negative way, as it was showcased through practical, real-life examples. The implementation of major renewable energy generation projects should be carried out in accordance with keeping system-scale effects and the necessities of consumers in mind.

Many opportunities are available to get more precise results of inertia loss. Running simulations on models with greater detail, such as distribution networks will enhance preciseness. Adding more tools to the simulation will also be of help, for example the use of solar PV and wind turbine regulator units.

The author’s aim in their future work is to examine industrial solutions and innovative projects, and their possible effect on power system stability.

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