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Small-Signal Stability of Power Systems in the View of the Connection of Renewable Energy Sources: An Albanian Case Study

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***Abstract*— Renewable energy sources (RES) has continued to expand and are considered to be the most efficient solution to the increase in electricity demand. The addition of RES, such as solar and wind power, brings with it new challenges to the operation and stability of the system. The integration of RES into the system affects the small-signal stability of the electrical network, and stability can serve as a criterion that limits the penetration level of these sources. In this paper, the small-signal stability of the Albanian power system is analyzed when adding RES (solar panels and wind turbines) to the existing network with only hydropower plants (HPP). The Albanian power system is built in the Neplan software and four different study cases have been simulated, which include small-signal stability in the current case, with addition of photovoltaic panels, with wind turbines and in the case where we have a hybrid supply. The analysis is based on the calculation of the eigenvalues and the participation factor for the above cases, drawing some conclusions about the impact on the small-signal stability, that will be slighty improved when these sizes of RES are connected to the network. The results of this study serve to build strategies for successfully integrating RES for a future sustainable system.**

***Keywords*—small-signal stability, renewable energy sources, eigenvalue, participation factor.**

I. INTRODUCTION

The electricity crisis that has affected the whole world, including Albania, has increased the focus for numerous investments in producing electricity from other alternative renewable sources that are eco-friendly to the environment. One of the fastest and most widespread ways to produce electricity are photovoltaic panels and wind energy, because, besides being RES, they do not pollute the environment, thus reducing air pollution and affecting the social and economic well-being of the state [1].

Due to its geographical position, Albania has great potential for the production of this form of energy. The number of sunny days in this region is quite high and promising and varies in a range from a minimum of 1100 kWh/m^2 to a maximum of over 1700 kWh/m^2, while the potential for wind is also very high with an average wind speed between 3.3m/s and 9.6m/s, referring to the IRENA report [2]. Regarding the benefits of wind and solar generation in Albania, a large number of projects are under construction and in the application and study stage for an even larger amount. In addition to covering the energy demand deficit, these projects also will cause and affect technical operations such as frequency oscillation [3], voltage stability [4], transient stability [5], [6], and small signal stability.

The small-signal stability of the system is very important and the reason for the choice of this study is based on the high projection values that are predicted for the connection of asynchronous generation in Albania until 2030. According to the study reports by CESEC of IRENA [7], the scenario for 2030 foresees an installed wind generation capacity of 616 MW, with an annual energy production exceeding 1,794 GWh. For solar power, the projected installed capacity is 1,074 MW, with an estimated annual generation of 1,697 GWh. All this high amount of RES that is expected to be connected in the Albanian electric power system will change the mode of operation of the system, which until now has been 100% from synchronous generators thus ensuring a high inertia and reserve of stability.

The investigation of small signal stability in the existing networks of different countries with low-inertia or “no inertia” [8] has led to the determination of many methods that realize the maintenance and improvement of the stability of these networks. These systems with high penetration from RES, which cover almost all the demand for energy, have a high dependence on atmospheric conditions, which also affect the stability of the system [9]. The addition of different types of energy storage sources to eliminate or reduce the rapid changes that RES have in energy production has a significant impact also on the small-signal stability of the system where it is connected [10]. In the paper [11], the authors looked at the impact on the small-signal stability of the system with pv sources for different control parameters in a phase-locked loop controller for a converter, but this study also refers to existing systems with low stability. Also, authors at [12], have carried out a review of all the articles that analyze the methods of including power oscillation damping (POD) for PV inverter to improve the stability of the system. The conclusion has been reached that the stability of the rotor angle of the synchronous generators depends on the penetration value of the photovoltaic plants. In [13], the authors have carried out an analysis of the

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system with HPP characterized by ultralow-frequency oscillation modes that by adding a PV plant in the right way we can have a strong impact on increasing the damping ratio for these modes.

Another important factor that affects small-signal stability is the operating conditions of the system and this has been analyzed in the North American Power Grid with high penetration of RES in the two extreme cases of load change which is the minimum and the maximum using Era model analysis [14]. The impact of wind turbines in these systems can be very large and it depends on the model [15], their control schemes, and the point of their connection to the grid [16]. The impact of the RES connection site's ideal point on small-signal stability should also be taken into consideration in certain nations with extremely high RES penetration rates [17].

The addition of RES, distributed generation, smart loads, and smart technology has led to the creation of many networks to function as microgrids but are facing challenges regarding their stability [18] and other phenomena such as resonance [19]. All the above analyses refer to weak grids with low inertia, which are very different from the case of the Albanian electrical system.

The importance of this paper lies in the fact that the Albanian electricity system is still dominated by hydropower plants, thus ensuring a high inertia, but many new renewable energy projects are being built and many other permits have been granted to build. Investigation of small-signal stability in this expected transition and transformation phase will include analysis of the impact of renewable energy sources from stability point of view in addition to energy production.

This paper is divided into 5 sections, where in the 2nd section the small signal stability approach, eigenvalues, autovectors, etc. are presented, in the 3rd section a presentation of the electrical system and its characteristics and the case studies to be analyzed are specified, in the 4th section the results and their analysis are presented, and in the 5th conclusions from the analysis are presented.

II. SMALL-SIGNAL STABILITY APPROACH AND METHODOLOGY ADOPTED

A. Proposed Methodology

The methodology applied in this study relies on real operational data obtained from the national Transmission System Operator, ensuring an accurate representation of the Albanian power system. The network is modeled and simulated in Neplan software, taking into account its distinctive structure, where electricity generation is almost entirely based on hydropower. Several case studies are developed to reflect different operational conditions with target levels of renewable integration. The small-signal stability of each case is assessed through eigenvalue analysis and Lyapunov's direct method, based on system linearization. The results are compared to identify the configuration that offers the most favorable dynamic behavior. Furthermore, the findings are discussed in the context of existing literature, emphasizing the particularities of the Albanian system and the contribution of this work to the broader research landscape.

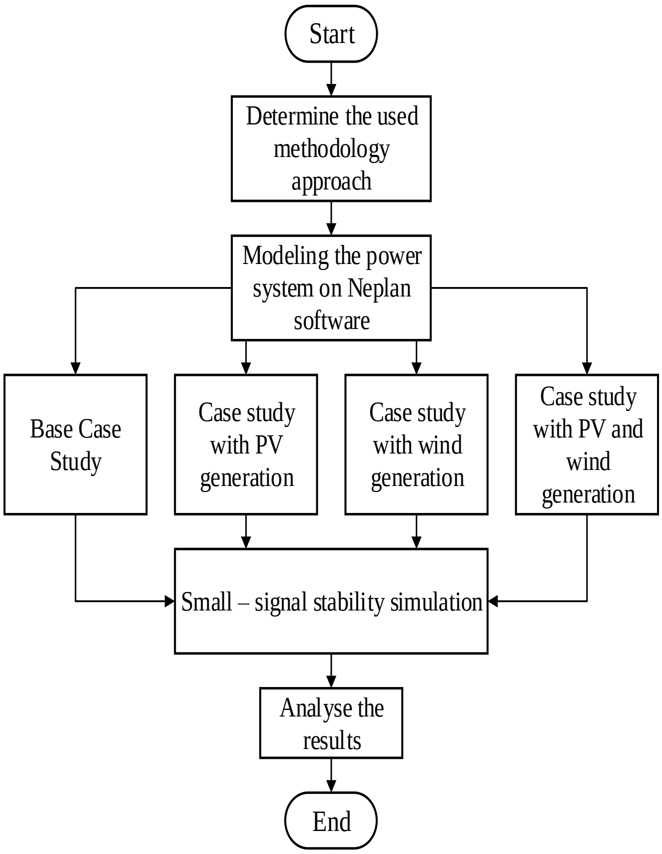

Fig 1. Flow chart of the used methodology

B. Small-Signal Stability

The system is called statically stable if it returns to the same statically stable state after a small excitation occurs. This means that any minor deviation from the equilibrium will not cause the system to diverge, but will eventually settle back to its original condition. This definition, expressed in mathematical terms, is represented by the following identity:

$$\lim_{t \to \infty} \Delta y(t) = 0 \qquad (1)$$

When a small disturbance occurs in the operating state of the system, the non-linear equations describing the dynamics of the system can be linearised. Such disturbances are common and occur frequently in power systems; for example, the most typical case is the daily load variation due to changing consumer demand over time.

In the power system, static system stability is of two types:

- Local phenomenon where one or more generators oscillate against the system.
- The global phenomenon is the case when groups of generators are oscillating against each other.

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In order to study the stability of small signals, the process of linearisation of the equations is carried out at the beginning. The equations are as follows:

$$\Delta \dot{x}o = [A]\,\Delta x + [B]\,\Delta u \qquad (2)$$
$$\Delta y = [C]\,\Delta x + [D]\,\Delta u$$

Where:

Δx, Δu, Δy are vector which corresponds to the state vector, intput vector, and the output vector

[A], [B], [C], [D] are matrix which corresponds the state matrix, input, output and feedforward matrix.

The solution of the above equation is obtained by the Laplacian transformation, leading to the values $\lambda_i = \alpha_i \pm j\omega_i$, which are known as the eigenvalues of the matrix A.

The stability of the system is evaluated according to Lyapunov's method, where the stability of the system is evaluated depending on the eigenvalue values and this analysis is presented in Tab 1.

Table 1. Stability of power system based on real part of eigenvalue

Eigenvalue	Real part	Power System
$\lambda_i = \alpha_i \pm j\omega_i$	negative	Stable
$\lambda_i = \alpha_i \pm j\omega_i$	possitive	Unstable
$\lambda_i = \alpha_i \pm j\omega_i$	zero	Is not determined in general

The real part of the eigenvalues represents the damping of the oscillation of the system, which is expressed by the following formula:

$$\zeta_i = \frac{\alpha_i}{\sqrt{\alpha^2 + \omega^2}} \qquad (3)$$

By analyzing the imaginary part of the eigenvalues, the frequency of oscillation can be determined:

$$f = \frac{\omega}{2\pi} \qquad (4)$$

C. Eigenvector and participation factor

For each eigenvalue $\lambda_i = \alpha_i \pm j\omega_i$ there is an associated eigenvector ϕi (the i-th column of the modal matrix), which is the solution of the equation and is known as the right vector of eigenvalues of [A]. This vector defines the mode shape of the oscillation and indicates which state variables have the greatest contribution to the corresponding mode.

$$[A] * \phi_i = \lambda_i * \phi_i \quad \text{for i= 1, 2 ……n} \qquad (5)$$

Similarly, the i-dimensional vector that satisfies the following mathematical relation is called the left eigenvector associated with the eigenvalue. Together with the initial state parameters, it determines the amplitude of the oscillations and provides information about their stability.
In power system analysis, left eigenvectors are particularly useful in identifying the participation of state variables in specific modes of oscillation, and they complement the right eigenvectors in forming the modal matrices used for system sensitivity studies and control design. Their interpretation can offer insight into how different components contribute to a given dynamic response.

$$\psi_i * [A] = \lambda_i * \psi_i \quad \text{for i= 1, 2 ……n} \qquad (6)$$

Combining these two vectors gives another concept known as the participation factor. This is a matrix [P] which has the following form:

$$\boldsymbol{P} = \begin{bmatrix} \boldsymbol{p_{i1}} \\ \boldsymbol{p_{i2}} \\ \cdot \\ \cdot \\ \boldsymbol{p_{in}} \end{bmatrix} = \begin{bmatrix} \phi_{i1} * \psi_{i1} \\ \phi_{i2} * \psi_{i2} \\ \cdot \\ \cdot \\ \phi_{in} * \psi_{in} \end{bmatrix} \qquad (7)$$

The elements of this matrix $\boldsymbol{p_{ik}} = \phi_{ik} * \psi_{ik}$ are known as the participation factor and, together with the eigenvalues, express the oscillations using the following equations:

$$\boldsymbol{x_k(t)} = \boldsymbol{p_{1k}e^{\lambda_1 t}} + \boldsymbol{p_{2k}e^{\lambda_2 t}} + \cdots + \boldsymbol{p_{nk}e^{\lambda_n t}} = \textstyle\sum_{k=1}^{n} \boldsymbol{p_{jk}e^{\lambda_i t}} \qquad (8)$$

The participation factors are generally indicative of the relative perticipations of the respective states in the corresponding modes.

III. CASE STUDY

In this paper, the Albanian power system has been chosen for implementation. Up to now, it has only been supplied by the synchronous generators of the hydropower plants. Because of this heavy reliance on water flows from snowfall and rainfall, it might be challenging to meet the demand for energy throughout the summer.

The high nominal voltages that are present in this system are 400 kV, 220 kV, 154 kV and 110 kV. In the initial system, the total generation is 1409.942 MW active power and 405.435 MVAr reactive power, also the imported is 92.942 MW and 120.129 MVAr. The hydropower plants constructed in Albania's north, such as the HPP of Koman, Vau Dejes, and Fierza, are the biggest and meet the most energy demand.

In this paper, four case studies are presented where small signal stability tests were performed:

- Initial power system
- Adding 200 MW PV source in 220kV
- Adding 200 MW of wind sources at 220 kV
- Adding 200 MW PV and wind at 220 kV

This value of RES penetration was chosen since it is the closest value that our system can cope with in these years. In future years, this value will begin to rise even further.

Figure 2 shows a schematic representation of the electricity system of Albania, but the system under consideration with several voltage levels consists of many layers built in Neplan software. The production of RES is variable due to their reliance on atmospheric conditions [20]. However, the combination of wind and photovoltaic (PV) generation partially mitigates the oscillations experienced by each source.

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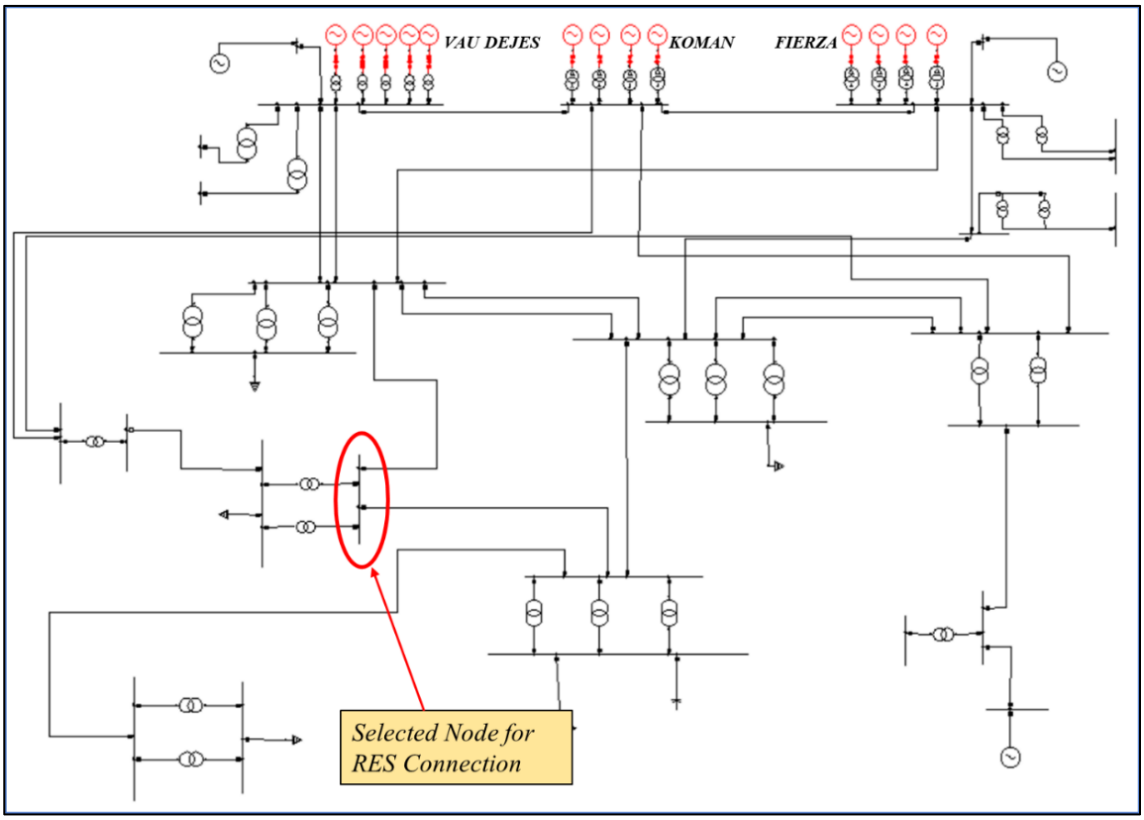

Figure 2. Schematic design of the Albania Power System

IV. RESULTS AND ANALYSIS

The results of the simulations have been evaluated. In the four simulated cases the number of eigenvalues is large and they are filtered and are considered only the eigenvalues with low damping ratio (i.e. lower than 20%). It should also be noted that the impact on small stability also depends on the RES connection point, its type, used technology, inverter type and RES penetration level, etc.

Figure 3 below shows the location of the eigenvalues selected with the smallest damping ratio for all case studies.

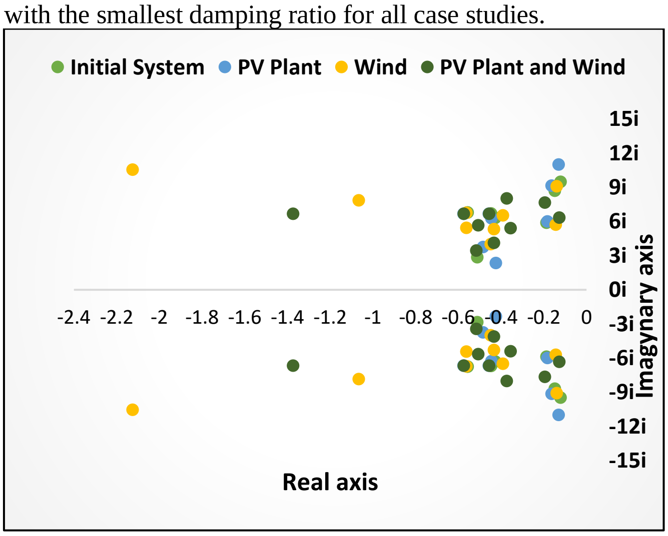

Figure 3. The allocation of the selected eigenvalue

The results for all cases recieved by the neplan software are summarised in Tab 2.

From the results obtained from simulation, it can be seen that the system is stable in the four case studies since all eigenvalues have a negative real part. The existing system contains only synchronous generators of HPP and the parameter δ (rotor angle) of synchronous generators of the largest HPP contributes more at the eigenvalues in this case. The maximum damping constant time for the existing system is 8.26 s, which is the time required for the vibration to dissipate and for the system to return to a stable condition. In the case study two when a 200 MW PV plant is connected to the system, which represents about 15% of the active power generated by the existing system, the damping ratio is slightly increased compared with existing system. The system is stable, showing a slight increase in the small-signal stability reserve. With this level of PV plant penetration, the impact on small-signal stability is not significant.

The contrary situation shows the results for 15% wind penetration in the system, connected at a node with several turbines. The power system is stable, but looking at the critical eigenvalues, the stability is improved. The damping ratio is higher than in both the previous cases. It can also be seen that the contributing factor that affects this eigenvalue more is the angle of rotation and the wind turbines contribute less to this eigenvalue.

Compared to case study 2, the impact of wind turbines on the system is greater and improve its stability.

In the case four where we have connected to the system 100 MW of PV and 100 MW of wind generation, it is seen that again the small signal stability is improved in the case of the Albanian power system. The damping ratio is at higher values compare with the previows scenarios, also the damping time constants and oscillatory frequency of the system under study are reduced, which means that when a disturbance occurs in the system, the system returns to a stable state for a faster time and the oscillations last for less time.

Similarly, the rotor angle of the largest synchronous generator in the Albanian power system is the factor that influences the oscillations more in this case. From the observation of the participation factor are the synchronous generator of Fierza HPP which have the greatest impact on the system oscillations at the eigenvalue with the smallest damping ratio for the four cases. Although there is a little improvement, it should be noted that the penetration of this sort of value of RES has no appreciable effect on the Albanian Power System's small-signal stability.

Table 2. Eigenvalues results with damping value ratio less than 20%

Case Study	Eigenvalue	Frequency (Hz)	Damping Ratio (%)	Damping Time Constants (s)	Dominant States
Initial System	-0.121 ± j 9.49	1.511	1.27%	8.26	δ of G4 HPP Fierza
	-0.147 ± j 8.701	1.386	1.69%	6.80	δ of G1 HPP Vau Dejes
	-0.187 ± j 5.887	0.937	3.17%	5.35	δ of G2 HPP Fierza
	-0.446 ± j 6.708	1.068	6.63%	2.24	δ of G4 HPP Koman
	-0.426 ± j 6.312	1.005	6.73%	2.35	δ of G3 HPP Koman
	-0.511 ± j 2.847	0.453	17.67%	1.96	δ of G1 HPP Fierza
	-0.556 ± j 6.768	1.078	8.19%	1.80	δ of G4 HPP Vau Dejes
	-0.557 ± j 6.768	1.078	8.20%	1.80	δ of G1 HPP Koman
With PV Plant	-0.129 ± j 10.996	1.751	1.17%	7.75	δ of G4 HPP Fierza
	-0.162 ± j 9.133	1.454	1.77%	6.17	δ of G1 HPP Vau Dejes
	-0.182 ± j 6.001	0.956	3.03%	5.49	δ of G2 HPP Fierza
	-0.424 ± j 2.351	0.374	17.75%	2.36	δ of G4 HPP Koman
	-0.445 ± j 6.273	0.999	7.08%	2.25	δ of G3 HPP Koman
	-0.456 ± j 6.661	1.061	6.83%	2.19	δ of G1 HPP Fierza
	-0.483 ± j 3.761	0.599	12.74%	2.07	δ of G4 HPP Vau Dejes
	-0.575 ± j 6.669	1.062	8.59%	1.74	δ of G1 HPP Koman
WIND	-0.138 ± j 9.096	1.448	1.52%	7.25	δ of G4 HPP Fierza
	-0.143 ± j 5.717	0.910	2.50%	6.99	δ of G1 HPP Vau Dejes
	-0.391 ± j 6.515	1.037	5.99%	2.56	δ of G2 HPP Fierza
	-0.433 ± j 5.308	0.845	8.13%	2.31	δ of G4 HPP Koman
	-0.448 ± j 4.009	0.638	11.11%	2.23	δ of G3 HPP Koman
	-0.561 ± j 5.441	0.866	10.26%	1.78	δ of G1 HPP Fierza
	-1.066 ± j 7.858	1.251	13.44%	0.94	δ of G4 HPP Vau Dejes
	-2.125 ± j 10.54	1.678	19.76%	0.47	δ of G1 HPP Koman
With PV Plant + Wind	-0.126 ± j 6.335	1.009	1.99%	7.94	δ of G4 HPP Fierza
	-0.194 ± j 7.664	1.220	2.53%	5.15	δ of G1 HPP Vau Dejes
	-0.355 ± j 5.408	0.861	6.55%	2.82	δ of G2 HPP Fierza
	-0.372 ± j 8.019	1.277	4.63%	2.69	δ of G4 HPP Koman
	-0.432 ± j 4.115	0.655	10.44%	2.31	δ of G3 HPP Koman
	-0.455 ± j 6.67	1.062	6.81%	2.20	δ of G1 HPP Fierza
	-0.506 ± j 5.669	0.903	8.89%	1.98	δ of G4 HPP Vau Dejes
	-0.515 ± j 3.43	0.546	14.85%	0.15	δ of G1 HPP Koman
	-1.373 ± j 6.681	1.064	20.13%	0.73	δ of G3 HPP Vau Dejes

V. CONCLUSIONS

From the case studies considered for the Albanian system with penetration of RES resources in the value of about 15%, it is seen that increasing these resources to this extent has a slight positive impact on small signal stability. The most visible improvement through the analysis of the damping ratio is in the case when the sources of wind generation are connected, this positive impact is also

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observed in the damping time constants, which is reduced when the generation of RES wind the PV plant and the system returns to a stable state for a while shorter. In the four case studies based on the participation factor, the state variable associated to the rotation angle of synchronous of large HPP participates the most. While many other studies have shown negative effects on the small signal stability, we can conclude that the RES penetration in the Albanian power system will have positive effects on the small-signal stability. In the future, the value of RES integration in the system should be after the evaluation of small signal stability, voltage stability and dynamic stability. It must be said that RES penetration of 15% does not have any strong impact on small signal stability of power system, but we have a slight improvement of it. The impact on small signal stability depends on the nature of the RES, their size and the point of their connection to the network.

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