The Impact of Distributed Autonomous PV Installations on Critical Infrastructure in Crisis Situations

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ABSTRACT Ensuring a functioning critical infrastructure system is crucial for many industries, including energy. Due to the transformation of the energy sector, it is necessary to take into account the impact of the induced changes on critical infrastructure. The presented paper focuses on the assessment of the effects of small dispersed photovoltaic power plants (PV), which are gaining in popularity both in households and in other buildings. Specifically, it is an impact assessment within the emergence of island operation in the selected area with the aim of restoring power to the facilities included in the critical infrastructure system as soon as possible. The specificity of the considered small photovoltaic power plants is their autonomy and impossibility of control from the superior control system. The presented case study compares possible approaches to power recovery on the one hand and the impact of different levels of dispersed PV on the other. The results provide important conclusions for the expected development of the critical infrastructure system in connection with the increase in autonomous distributed electricity sources.

INDEX TERMS Critical infrastructure and energy, island operation, stability, distributed PV, autonomous PV.

NOMENCLATURE

CI Critical Infrastructure.
EC European Commission.
EHV Extra-High Voltage.
EU European Union.
HV High Voltage.
MARI Manually Activated Reserves Initiative.
MV Medium Voltage.
PICASSO The Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation.
PV Photovoltaics.
RES Renewable Energy Sources

I. INTRODUCTION

A. THE IMPORTANCE AND FUNCTIONING OF CRITICAL INFRASTRUCTURE IN THE CZECH REPUBLIC WITH A FOCUS ON THE ENERGY SECTOR

Critical infrastructure (CI) as an element of public space, economy and state security in the Czech Republic also functions as an important part of the state crisis management system. Amendment to Act 240/2000 Coll. [1] set out firm criteria for the selection, operation and protection of critical infrastructure elements.

According to Act No. 240/2000 Coll. [1] “Crisis management” means a CI element or a system of CI elements, the disruption of which would have a serious impact on the security of the state, the provision of basic living needs of the population, the health of persons or the economy of the state.

European CI means CI on the territory of the Czech Republic, the disruption of which would have a serious
impact on another Member State of the European Union [2].

The individual CI sectors are interdependent and use each other to perform their functions. Critically important sectors include, in particular, the production and supply of electricity, natural gas, water or telecommunications services. Due to the interconnectedness and wide structure (e.g. the energy or water system), critical infrastructure is very vulnerable.

When elements of CI are selected by central administrative authorities, the aspect of the societal importance of the element for maintaining key functions of the state or territorial unit is taken into account, operational and technical values and capacities of the given CI element are assessed as well as the possibility of interchangeability of elements [3].

Operators of CI entities have a number of important obligations under the law in the area of its safety and protection. This creates a presumption of a higher, but uniform level of CI within the Czech Republic. Operators are, for example, required to provide information to identify the CI element, to draw up a CI preparedness contingency plan, to designate a liaison security officer who communicates with central administrations for the CI element and also to submit to inspections by the relevant central administration [4].

The crisis preparedness plan of the CI entity identifies possible threats to the functioning of critical infrastructure elements, sets out comprehensive measures for its protection and measures to ensure the action capability of the entity to deal with crisis situations.

On the other hand, CIs may, in crisis situations, give priority to the supply of energy, materials and services to the extent necessary, and CI staff who are involved in ensuring its activities are exempt from work duties and other legal restrictions in crisis situations.

The operation and protection of CI, especially in the energy segment, has a strong link to raw material and energy security and ensures the basic tasks of the state in times of calm and in crisis situations.

The electricity system of the Czech Republic is a flat system with a large number of connections to the electricity systems of the surrounding states. An essential output of this CI sector is the provision of a sustainable and secure electricity supply also in the event of crisis situations or exceptional situations.

The task of science and research is to find new organizational procedures and technical solutions that would be able to eliminate the danger of blackout or mitigate its consequences. E.g. the research and design of a process model for the management of a power plant and distribution network in the event of a transmission network failure, or a process model for assessing the safety requirements of a territory in terms of energy.

B. THE LINK BETWEEN CRITICAL INFRASTRUCTURE AND RENEWABLE ELECTRICITY SOURCES

The transformation of the energy sector into a concept using carbon-free technologies brings with it a large number of new challenges that affect a wide range of areas [5]. The municipal challenge of “decarbonisation” is bringing ever greater social and economic pressure to accelerate the decommissioning of coal-fired power plants in particular and their replacement by other energy sources. To achieve the required reduction in CO2 production, the installed capacity of photovoltaic, wind and combined cycle power plants is being increased [6].

Regardless of the ongoing changes, we must not forget the basic requirements for the electricity system, which can be summarized in the following points:

- Security
- Reliability
- Availability
- Sustainability
- Durability

Our contribution focuses on the safety, reliability and resilience of the power system. The threat of Blackout is becoming more and more common in society. The recent Ernestinovo substation incident in January 2021 is proof of this [7]. A number of new concerns remain in connection with the transformation of the electricity sector, especially with selected risk consequences.

A high risk can be identified in the threat to the stability of interconnected power systems. The original concept of the power system based on centralized sources (coal and nuclear power plants) had extensive regulatory options (auxiliary and system services). Many sufficient means were available to control the power supplied to the system, and the most important variable factor was electricity consumption (depending on customer behavior). Due to the small share of renewables, in particular photovoltaic and wind farms in Europe, the factor of variable weather supply dependent on weather did not manifest itself to a significant extent [8].

The growing share of renewable electricity sources undeniably brings new risks associated with the stability of the system. In the area of auxiliary and system services, new solutions in the form of aggregated blocks [9], [10] and battery storage are being sought and implemented at the same time [11], [12]. Projects of this type are gradually being put into operation [13], [14]. On the other hand, in electricity systems, the factor of variable supply of electricity from renewable sources is becoming more and more important, which results in increased demands on ensuring stable operation of the systems [5]. To increase efficiency in the auxiliary services sector, the MARI and PICASSO projects are currently underway in Europe. The aim of these projects is to create a unified market for selected support services, which will increase the level of cooperation between individual transmission systems and support service providers and will also lead to economic efficiency. However, it is a lengthy and demanding process, as unification is needed across many participants, which show different local specifics [15].

What is the relationship between these changes and CI? Until now, in the event of major system failures, only traditional certified sources have been used, enabling the Black
Start function (a certified service provided by power plants in the process of restoring the functionality of generating units or a part of the electric system that allows operation independently of the distribution/transmission system) and the island operation function. These are resources that are fully under the control of the dispatch centre. The increase in the share of renewable dispersed results in an increase in the share of resources operating in the autonomous regime without control by dispatchers. Typically, these are small photovoltaic power plants in a low voltage system (roof installation) [16]. The main question is to what extent the rapid recovery of power to the critical infrastructure facility will be endangered.

EC Regulation “COMMISSION REGULATION (EU) 2016/631 of 14 April 2016 establishing a network code for requirements for the connection of generations to the electricity system” [17] lays down certain requirements in order to avoid adverse effects on newly installed diffuse electricity sources. The aim is therefore to assess whether these measures are sufficient.

C. PAPER ORGANIZATION
The paper is divided into six sections. The first two introductory sections focus on the importance and functioning of CI in the Czech Republic, the connection between critical infrastructure and renewable electricity sources and the formulation of basic hypotheses. The third section focuses on the description of the proposed methodology and the methods and tools used. The fourth part focuses on a case study that points to the process of black start and subsequent island operation for a selected area in order to provide power for critical infrastructure facilities. The first part of the case study will focus on the initial state without considering scattered RES, the second part considers scattered RES with the implementation of rules [17]. The fifth part is focused on the presentation and discussion of the obtained results. The last sixth part summarizes the conclusions and formulates basic recommendations.

II. HYPOTHESES
When modeling blackout emergencies in the system, namely the recovery of operation from a fault state, the application of production resources with a certified Black start function and the subsequent creation of a gradually expanding area operating in island mode (based on network codes and other regulations also appropriately certified resources) are usually considered [18]. On the load side of the system, the terminals or stations that supply the objects included in the CI system are gradually connected as a priority. There are some complications. At present, due to the fact that the switching elements of the distribution system are not 100% automated and remotely controlled, it is not possible to only connect consumption points included in the CI system. In practice, this means that the entire terminals or switching stations are connected during the renewal, which means that, in addition to the objects included in the critical infrastructure system, other customers are also connected. Restoring power to these customer’s places increased demands on available power and increases power recovery latency for lower-priority critical infrastructure facilities. Another risk lies in the consumption behavior of the aforementioned other customers.

The main question is how its facilities will behave in conditions of island operation, where there are more significant and more frequent changes in operating parameters, especially the frequency, mainly in relation to the functionalities specified in the Regulation [17] for non-synchronous production modules of category A. The issue is crucial for the reliable operation of a critical system, especially in island power mode during emergencies.

III. METHODOLOGY
A. MODEL FOR SOLVING MID-TERM DYNAMICS
The mathematical model is created in the Matlab-Simulink software and its aim is to investigate changes in voltage and frequency when connecting individual loads. It is a model of a gas turbine and generator, including the excitation and control system. The unit’s own consumption and output to the required distribution substations for powering critical infrastructure are modeled.

From the point of view of the created model, the most fundamental role is played by the control circuits - especially the excitation system and its alternator control, the gas turbine control system and the gas turbine speed control for island operation. The following lines will briefly describe the considered models. Fig. 1 shows the overall scheme of the model.

![Overall scheme of the proposed model.](image_url)

In the case of the excitation system, this is a simplified AC excitation model corresponding to the AC1A model according to IEEE standards [19]. This model respects the saturation of the auxiliary generator and does not contain a limit for the upper value $V_{f\max}$, which is implicitly included in the saturation parameters. The $V_{min}$ value is zero by default. The refinement of the exciter model is also being considered so that the influence of the damping circuits is respected. The model scheme is illustrated in Fig. 2.

Because the controllers of different manufacturers have different structures, based on the analysis of the structure of the most used controllers in our electricity system, a universal model of a generalized excitation controller was created, which allows to model real controllers [19]. Based on this model and certain simplifying assumptions, a simplified model of the exciter controller illustrated in Fig. 3 was built.

The considered dynamic model [20], [21] of a gas turbine is derived from the fact that the turbine power $N_{Turbine}$
The efficiency of the power plant is determined by the fuel calorific value and the internal thermodynamic efficiency $\eta_{TD}$. Calorific value and thermodynamic efficiency are considered constants. The power dependence on speed (self-regulating effect) is greater for a gas turbine than for a steam turbine due to the compressor. The turbine itself is modeled by the static characteristic $N_{\text{turbine}} = f(\text{fuel supply})$. The value of $M_0$ respects the power input of the compressor or friction losses. The $K_M$ parameter can be used to respect the static dependence of power on speed or ventilation losses. The $G_{\text{min}}$ parameter is the minimum fuel supply required for stable turbine operation. As a compressor power input can be less than the product of the turbine gain and the minimum fuel supply, the gas turbine has a braking power of $M_0 = G_{\text{min}} \cdot A_T$. The dynamics are respected by the control valve, in particular by the opening speed $v_{\text{max}}$ and the closing $v_{\text{min}}$, which can generally be different, the closing speed tending to be higher in absolute value. Furthermore, the model respects the dynamics of fuel and compressor supply. The considered gas turbine model is illustrated in Fig. 4.

For a specific control mode within island operation, it is still necessary to implement speed control of the turbine [22] according to Fig. 5.

The presented models, in terms of the dynamics of important elements, sufficiently reflect the real behavior of similar devices. For the purposes of the analysis of power recovery of critical infrastructure objects within the island operation, these models have sufficient accuracy.

**B. RENEWABLE ENERGY SOURCES MODEL**

For the model type defined above, there is a sufficient representation of the PV plant in the form of a controlled source of active power. However, due to the expected deviations of the system frequency, there is a need to implement the functionalities defined in the EC Regulation [17]. The regulation is defined separately for synchronous production modules and non-synchronous production modules (e.g. PV). Production modules are further classified into 4 categories A, B, C and D. Production modules of categories A, B, C are connected to voltage levels lower than 110 kV. Category A typically includes production modules corresponding to small PV installations - for example, roofs of family houses and other buildings. This category is also characterized by the fact that they work in autonomous mode without the reach of the relevant dispatching workplace. For each category of production modules mentioned regulation specifies a number of functionalities. For Category A production modules, the most important requirements are the operating time with system frequency deviations and changes in operating modes from certain system frequency thresholds.

At over-frequency, the output power of the production module should be gradually reduced. The activation threshold for this functionality can range from 50.2 - 50.5 Hz [17]. Activation must take place with a maximum delay of 2 seconds [17]. The limitation of the output power should take place with droop in the range from 2% to 12% [17]. Droop can be expressed according to (1).

$$s_2 = 100 \times \frac{\Delta P}{\Delta f/f_n} \times \frac{P_{\text{ref}}}{\Delta P}$$  

(1)

where $s_2$ is the droop in %, $\Delta f$ is the current frequency deviation in Hz, $\Delta f_{\text{nad}}$ is the frequency deviation when the threshold value is reached in Hz, $f_n$ is the nominal system frequency, $P_{\text{ref}}$ is the current reference active power in kW and $\Delta P$ is the required output power change in kW. Based on the current frequency value and the reference power, it is possible to define the required change (in case power reduction) for the entered droop value. The described functionality was integrated into the model described in previous section A.

At under-frequency, the output power of the production module should also be limited. However, the regulation specifies 2 thresholds for this case. Here, the definition of the required power change is somewhat different from the over-frequency functionality. When the frequency drops below 49.5 Hz, the output power of the production module should decrease by 10% of its maximum power for every 1 Hz deviation from the threshold value. When the frequency drops below 49 Hz, the output power of the production module should decrease by 2% of its maximum power for every 1 Hz deviation from the threshold value, so a smaller decrease is desirable for more significant sub-frequencies.
IV. CASE STUDY

The aim of the case study is to demonstrate the behavior of independently created island operation with the gradual renewal of power supply to critical infrastructure facilities. The case study looks at two crucial factors.

The first factor is the method of restoring power to individual objects of CI within the island operation. For this factor, it is necessary to consider 3 options for power recovery. The first option is to restore the power supply at the level of high voltage substations (transformer stations), where on the one hand there is a low number of switching operations, however, on the other hand, power changes may be a potential stability hazard for the control of a gas turbine production unit. The risk lies mainly in the potentially large deviations of the frequency of the created island system, i.e. when certain limit values are reached, the frequency protections of the gas turbine generation unit would act and the power recovery would fail. The second option is to restore power to individual switching stations, which may include multiple MV feeders. This process is a bit longer, but at the cost of reduced risk of adverse effects of large performance changes. In addition, this option allows, to a limited extent, to prioritize power recovery for CI facilities. The third option is to restore the power supply by individual MV feeders. Of these options, this is the lengthiest process. As for performance changes, they are less risky than in previous cases. In addition, a sufficient degree of prioritization of power recovery for CI facilities needs to be emphasized.

The second factor is the distributed production within the analyzed system, especially the installation of small PV plants, which operate in an autonomous mode and are currently rapidly gaining in popularity. Depending on the extent of their application, they can contribute to the occurrence of frequency deviations similar to the first mentioned factor (frequency increase) and bring the risks described above. For the needs of the case study, the proportion of PV power supply in relation to the consumption at individual feeders was considered as a variable.

A. DESCRIPTION OF THE STUDIED NETWORK AND SELECTION OF CRITICAL INFRASTRUCTURE OBJECTS

The case study was conducted in the area of the district town where the gas turbine power plant is located, enabling Black start and island operation. The studied area is represented by one production unit, three HV lines, two HV / MV transformer stations, 9 MV switching stations and 17 MV feeders. The electrical diagram of the studied area is shown in Fig. 6.

The key technological unit for crisis situations is the unit built on a natural gas combustion turbine with an electrical output of 43.2 MW, which has properties important especially for Black start and island operation. These features include operation at reduced natural gas pressure in the network, start with a minimum amount of external energy (provided by a diesel generator) and a wide range of control options. Electrical power is fed to the HV distribution system, which supplies 2 HV/MV substations (Substation A and Substation B) in the given area. The MV distribution system also consists of switching stations and individual feeders, which can be controlled automatically and remotely.

The nature of the load in the selected area needs to be viewed with a different approach in an emergency. In standard operation, the HV system is connected to other HV nodes (and EHV/HV nodes with a link to the transmission system) and power is fed into it from other power plant units in the given area. These conditions make it possible to safely and reliably cover the needs of all consumption points in the area. In the event of an emergency, assuming the loss of a synchronous connection with the HV system, HV/HV nodes and other generation units, limited power is available for the given area, limited by the turbine power. The main goal is therefore the fastest possible resumption of electricity supply, preferably for CI facilities.

For the given area, we performed an analysis and selected feeders providing power supply for objects included in the CI with three levels of priority (key, important, other). The case study assumes the smallest unit of the output due to network characteristics. The fact that the possibility of automatic and remote control is available at the feeders led us to this step. However, the optimal situation would be that it is possible to switch on only the consumption points supplying CI objects during an emergency. However, it would be necessary to automate each distribution substation within the distribution system. In the analyzed case, in addition to the restoration of power supply to the supply points supplying the CI objects, the power supply will also be restored at other supply points falling under the given feeder. This is a compromise solution, in which the compromise is between the degree of automation of the MV distribution system and the available power during an emergency.

Table 1 summarizes the parameters of individual feeders - maximum power consumption, priority and affiliation under a specific HV / MV substation and MV switching station.

B. SCENARIOS

Four scenarios were identified for the case study, taking into account the different approach to power recovery for selected
TABLE 1. Parameters of outlets supplying objects included in the critical infrastructure system.

| Substation code | Switching station code | Feeder code | P [MW] | Q [MW] | Priority |
|------------------|------------------------|-------------|--------|--------|----------|
| A                | A_1                    | A_1_1       | 1.204  | 0.935  | Key      |
| A                | A_1                    | A_1_2       | 0.307  | 0.258  | Key      |
| A                | A_2                    | A_2_3       | 0.722  | 0.561  | Key      |
| A                | A_2                    | A_2_1       | 0.085  | 0.066  | Key      |
| A                | A_2                    | A_2_2       | 0.722  | 0.561  | Key      |
| A                | A_1                    | A_1_3       | 1.322  | 1.026  | Key      |
| B                | B_1                    | B_1_1       | 1.896  | 1.472  | Key      |
| B                | B_2                    | B_2_1       | 0.871  | 0.676  | Key      |
| B                | B_3                    | B_3_1       | 1.105  | 0.858  | Key      |
| A                | A_3                    | A_3_1       | 0.361  | 0.28   | Important|
| A                | A_2                    | A_2_4       | 0.255  | 0.198  | Important|
| A                | A_4                    | A_4_1       | 1.226  | 0.952  | Important|
| B                | B_4                    | B_4_1       | 0.49   | 0.38   | Important|
| B                | B_3                    | B_3_2       | 0.878  | 0.682  | Important|
| B                | B_4                    | B_4_3       | 0.287  | 0.223  | Important|
| A                | A_5                    | A_5_1       | 2.962  | 2.299  | Other    |
| B                | B_4                    | B_4_2       | 0.732  | 0.568  | Other    |

TABLE 2. Characteristics of the scenario no. 1 and no. 2.

| Substation code | Feeder code | Switch on time [s] | P [MW] | Q [MW] |
|-----------------|-------------|--------------------|--------|--------|
| A_3_1           | 1.204       | 0.935              | Key    |
| A_2_4           | 0.307       | 0.258              | Key    |
| A_4_1           | 1.226       | 0.952              | Important|
| B_4_1           | 0.49        | 0.38               | Important|
| B_3_2           | 0.878       | 0.682              | Important|
| B_4_3           | 0.287       | 0.223              | Important|
| A_5_1           | 2.962       | 2.299              | Other   |
| B_4_2           | 0.732       | 0.568              | Other   |

TABLE 3. Characteristics of the scenario no. 3.

| Substation code | Switching station code | Power on time [s] | P [MW] | Q [MW] | Priority |
|-----------------|------------------------|-------------------|--------|--------|----------|
| A_1_1           | 1.204                  | 0.935             | Key    |
| A_1_2           | 0.307                  | 0.258             | Key    |
| A_2_3           | 0.722                  | 0.561             | Key    |
| A_2_1           | 0.085                  | 0.066             | Key    |
| A_2_2           | 0.722                  | 0.561             | Key    |
| A_1_3           | 1.322                  | 1.026             | Key    |
| B_1_1           | 1.896                  | 1.472             | Key    |
| B_2_1           | 0.871                  | 0.676             | Key    |
| B_3_1           | 1.105                  | 0.858             | Key    |
| A_3_1           | 0.361                  | 0.28              | Important|
| A_2_4           | 0.255                  | 0.198             | Important|
| A_4_1           | 1.226                  | 0.952             | Important|
| B_4_1           | 0.49                   | 0.38              | Important|
| B_3_2           | 0.878                  | 0.682             | Important|
| B_4_3           | 0.287                  | 0.223             | Important|
| A_5_1           | 2.962                  | 2.299             | Other   |
| B_4_2           | 0.732                  | 0.568             | Other   |

TABLE 4. Characteristics of the scenario no. 4.

| Substation code | Switching station code | Power on time [s] | P [MW] | Q [MW] | Priority |
|-----------------|------------------------|-------------------|--------|--------|----------|
| A_1_1           | 1.204                  | 0.935             | Key    |
| A_1_2           | 0.307                  | 0.258             | Key    |
| A_2_3           | 0.722                  | 0.561             | Key    |
| A_2_1           | 0.085                  | 0.066             | Key    |
| A_2_2           | 0.722                  | 0.561             | Key    |
| A_1_3           | 1.322                  | 1.026             | Key    |
| B_1_1           | 1.896                  | 1.472             | Key    |
| B_2_1           | 0.871                  | 0.676             | Key    |
| B_3_1           | 1.105                  | 0.858             | Key    |
| A_3_1           | 0.361                  | 0.28              | Important|
| A_2_4           | 0.255                  | 0.198             | Important|
| A_4_1           | 1.226                  | 0.952             | Important|
| B_4_1           | 0.49                   | 0.38              | Important|
| B_3_2           | 0.878                  | 0.682             | Important|
| B_4_3           | 0.287                  | 0.223             | Important|
| A_5_1           | 2.962                  | 2.299             | Other   |
| B_4_2           | 0.732                  | 0.568             | Other   |

CI facilities, with partial cases of proportional representation of small PV plants being analyzed for each scenario.

The first and second scenarios consider power recovery at the level of HV stations. This scenario is characterized by the fact that the power recovery process takes place in a short time (within 5 minutes from the start-up of the gas turbine generation unit). In terms of power changes, these are relatively large for these scenarios (maximum 11.6 MVA or 9.17 MW), which may pose a risk of frequency protection of the generation unit, which would frustrate the renewal process. The first scenario considers first switching on station B and then station A. The second scenario first considers switching on station A and then station B. Switching times for scenarios 1 and 2, including the power of individual HV stations, are summarized in Table 2.

The third scenario considers the renewal of power supply at the level of MV stations. Compared to the first two scenarios, the renewal process will take longer - 15 minutes from the start-up of the gas turbine generation unit. As for the power changes, they are less significant for this scenario compared to scenarios 1 and 2 (maximum 3.75 MVA and 2.96 MW, respectively). The risks associated with the effect of frequency protections and system disturbances are therefore significantly lower for this scenario than for scenarios 1 and 2. Switching times for scenario 3, including power consumption falling under individual MV switching stations, are summarized in Table 3.

The last fourth scenario considers the renewal of power supply at the level of MV feeders. For this scenario, the recovery process is estimated to be 30 minutes from the start of the gas turbine production unit. As far as power changes are concerned, the maximum power change is similar to scenario 3, i.e. a maximum of 3.75 MVA, resp. 2.96 MW. The risks of this scenario are similar or rather smaller than in scenario 3. The switching times for scenario 4, including the power consumption falling under the individual MV feeders, are summarized in Table 4.

For the purposes of assessing the impact of small PV plants within the study area, the case study considers different levels of representation for each scenario. The power of the PV plant within a certain unit (depending on the scenario - HV stations (scenarios 1 and 2), MV switching stations (scenario 3) and MV terminals (scenario 4)) is defined on the basis of multiplying the active power of the selected unit. An example is the total output of PV within the MV output A_1_1 at a representation rate of 10%. The active power for a given feeder is 1204 kW according to Table 1. The power of the PV plant is therefore determined by multiplying the value of the active power by the value of the degree of representation - 1204 kW * 10% = 120.4 kW. In the case of dispersed PV plants within the study area, it is necessary to take into account other specific feature and the time required to resynchronize the inverter in order to resume supply to the
grid. For the purposes of the case study, a time of 60 seconds was considered.

V. RESULTS AND DISCUSSION

For the mathematical model created in the Matlab-Simulink software, simulations were performed for the specified scenarios and the degree of representation of small PV plants in the analyzed system. The evaluation was based on two approaches. The first approach is based on the evaluation of the power balance, which aims to point out the active power and power factor during island operation with the gradual connection of critical infrastructure facilities and during the gradual resynchronization of small PV plants connected in the analyzed system. These results will provide an idea of the use of the generation unit with a gas turbine and possible other options to meet the needs of CI facilities in a much larger area. The second approach is based on the evaluation of the system frequency of the generated island operation, which is affected by the connected loads (CI objects) and resynchronized small PV plants. This approach is aimed at detecting possible failures associated with the stability of the system and the possible operation of the protective systems of the gas turbine generation unit.

For clear visualization, only the representation of small PV plants at the level of 0, 20, 40 and 60% are visualized for graphic outputs. Achieving a higher proportion of small PV plants is unlikely due to the nature of the connected supply points.

A. ACTIVE POWER EVALUATION

Fig. 7 illustrates the curves of active power at the HV output of the generation unit with a gas turbine for individual scenarios and selected proportions of distributed PV plants. Scenarios 1 and 2 show significant power changes both when connecting individual consumption and when resuming the power supply of dispersed PV plants. Scenarios 3 and 4 do not have such significant performance changes, but in these scenarios, with a higher proportion of small PV plants, more significant transients occur. The cause of this phenomenon is the power band in which the production unit moves - 0.5 MW compared to the nominal power of the machine 43.2 MW. These results indicate the potential use of a given production unit for island operations supplying CI in a much larger area. However, the risk lies in the variable nature of the power supplied by distributed PV plants.

Fig. 8 illustrates the power factor waveforms at the MV output of a gas turbine generation unit for individual scenarios and selected proportions of dispersed PV plants. The illustrated power factor is estimated based on gas turbine generator output active and reactive power. The generation unit also supplies all reactive power to the network defined by the island operation. It can be seen from the figure that if the proportion of dispersed PV plants increases, the power factor deteriorates. The reason is the nature of the behavior of inverters dispersed by PV, due to the fact that Q/U regulation does not apply to them. Each feeder consumes reactive power which must be supplied to the network. In this case, there is just one option - supplying reactive power by gas turbine generator. This is the main reason why the power factor is less than 0.8 in all cases.

Excessive consumption of reactive power in a defined part of the network can lead to other potential problems threatening the stable operation of the island system.

B. SYSTEM FREQUENCY EVALUATION

For each performed simulation (for scenarios 1 - 4 and different levels of representation of small PV plants), the extremes of the network frequency were evaluated. They are summarized in Table 5.

Based on the results summarized in Table 5, it can be stated that in scenarios 1 and 2, at certain moments the network frequency will fall below the permissible threshold value for the frequency protection of the production unit - 48.5 Hz. In practice, this phenomenon would lead to the failure of island operations and thus to the resumption of power to CI facilities. In the case of the effects of small PV plants, it can
be stated that they momentarily contribute to the increase of the network frequency but without the risk of reaching the threshold value for the effect of frequency protection. From the point of view of extreme frequency values, it is therefore possible to recommend the process of restoring the power supply of CI objects in the selected area according to scenarios 3 and 4.

Fig. 9 to Fig. 12 show the statistical evaluation of the frequency in the form of histograms for all scenarios and selected values of the degree of representation of scattered PV within the analyzed area. For all datasets, the same length of 30 minutes was used and the frequency values were determined with a resolution of 10 ms.

Fig. 9 and Fig. 10 demonstrate the already mentioned significant decreases in system frequency, which are the result of large power changes within the analyzed island operation. From the above figures, it is possible to observe an increase in frequency due to the reconnection of dispersed...
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FIGURE 11. Statistical evaluation of system frequency for scenario 3 for different proportions of small PV plants.

FIGURE 12. Statistical evaluation of system frequency for scenario 4 for different proportions of small PV plants.

PV plants, which, however, is not so significant. Fig. 11 and Fig. 12 demonstrate lower frequencies and smaller frequency deviations in scenarios 3 and 4.

C. DISCUSSION AND OVERALL EVALUATION

The results presented in the previous sections predetermine scenarios 3 and 4 for practical use. Within these scenarios, frequency deviations do not occur outside the permitted limits, thus avoiding the frequency protection of the production unit and creating favorable conditions for gradual power recovery at individual CI facilities. It is debatable which of the recommended scenarios should be preferred. Scenario 3 requires 15 minutes to restore power to the production unit operating in island mode. Scenario 4 requires twice the time - 30 minutes. However, in Scenario 4, there is a greater risk of a longer delay because the recovery process is more complex, requiring a larger number of operations involving a significant number of components that can potentially fail.

Distributed small PV plants characterized by an autonomous operating mode (without the possibility of intervention by the dispatching workplace) and after a mains power failure and its resumption, they are automatically synchronized with the grid and electricity supply is restored. The results of the case study show that they do not have significant negative effects in the gradual renewal of power supply to CI facilities and other facilities dispersed by the PV power plant, even at higher levels of representation. Due to the short duration of frequency deviations, the functionalities described in subsection III.B do not even apply within the analyzed process. On the contrary, these functionalities would be fully reflected in the beginnings of the emergency - significant and persistent frequency deviations, which in an unfavorable case precedes the Blackout state.

VI. CONCLUSION

The paper aims to address the issue of the functional system of critical infrastructure in the context of the transformation of the energy sector. More specifically, the paper focuses on analyzing the impacts of distributed generation (small PV systems) through the use of a mid-term islanded grid dynamics model with a focus on critical infrastructure assets. For the analysis, a mathematical model of mid-term dynamics implemented in MATLAB Simulink was used. The developed model consists of sub-models of the synchronous generator, the excitation system model including control, the gas turbine model including control, the model of a defined part of the grid under islanded operation and the dispersed generation model, which takes into account the requirements of the regulation [17]. Simulations were performed for several different scenarios and the results were then evaluated.

The evaluation of the results of the case study brings the following findings:

• In terms of reliable operation in the island mode for the selected area, the procedures according to scenarios 3 and 4 (rather scenario 3) are recommended.
Scattered PV within the analyzed system do not have a significant effect on the stability of island operation for the given case.

The functionalities set out in the Regulation [17] will not be more pronounced, as the frequency deviations caused by the connection of off-take in island operations last only a very short time corresponding to the dynamic characteristics of the production unit under consideration.

The potential risk is the conditions regarding the reactive power, which in the case of an increasing proportion of dispersed PV plants becomes predominant over the active power, which may be a risk in terms of the working area of the alternator supplying the island operation.

The application of the results of this work is important in the planning processes of emergency preparedness for widespread power outages, which would ultimately lead to resilience of critical infrastructure.

Further research could potentially expand the area of islanding, i.e., a more complex system, considering the different behaviour of different types of PV inverters, or possibly analyse crisis conditions preceding a Blackout condition - i.e., conditions where significant and persistent deviations of operating variables occur.

APPENDIX I. SIMULATION PARAMETERS
See Table 6.

APPENDIX II. MODEL EQUATIONS
Exciter and exciter controller could be described by equations (2) – (7). Gas turbine and gas turbine controller could be described by equations (8) – (16).

\[
\frac{C_{EX} - I_f k_D - V_e A_{SS} B_s V_e}{1 + s T_A} - \frac{k_A}{1 + s T_A} = V_e \\
\frac{k_C h_f}{V_e} = V_f \\
(V_{set} - V_{gen}) \left( kp + \frac{1}{s T_I} \right) = C_{EX} \\
V_{setmin} < V_{set} < V_{setmax} \\
V_{Delta}^{min} < (V_{set} - V_{gen}) \frac{1}{s T_I} < V_{Delta}^{max} \\
V_{Cmin} < (V_{set} - V_{gen}) (kp + \frac{1}{s T_I}) < V_{Cmax} \\
C_{Turbine} \left( 1 - \frac{1}{T_f} \frac{1}{1 + s T_C} \right) = M_T \\
(M_T - M_0) A_T - s_{Gen} k_M \\
\]

\[
N_{Turbine} \left( 1 + s T_D \right) = \frac{1}{u_{GT}} \left( 1 + s T_{EPH} \right) < G_{max} \\
\]

\[\begin{align*}
C_{Turbine} (1 - \frac{1}{T_f} \frac{1}{1 + s T_C}) & = M_T \\
\frac{1}{1 + s T_{EPH}} & = \frac{1}{u_{GT}} \\
\omega & = 1 + s_{Gen} \\
0 < \frac{1}{1 + s T_{EPH}} & < G_{max} \\
0 < (\omega_{set} - \omega - u_{GT} b_p) \frac{1}{s T_I} & < G_{max}
\end{align*}\]

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