International Journal of Reliability, Risk and Safety: Theory and Application

Online ISSN: 2676-3346

OPEN ACCESS

Vol. 7/ Issue 2/ Year 2024/ pp. 116-132
DOI: 10.22034/IJRRS.2024.7.2.11
Received: 03 November 2024, Revised: 31 December 2024, Accepted: 31 December 2024

Available online at: https://www.ijrrs.com

Original Research Article

Microgrids and the Stability of Electric Power Systems – the Case of Bosnia and Herzegovina

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Abstract

The increasing participation of RESs in electricity generation has increased the complexity of the required OR capacity as a basis for the stability and resilience of EPSs. The variability of electricity generation in PPPs, WPPs and SHPPs affects the variability of the required reserve of electricity generation in the EPS. Therefore, the probability tool, i.e., with statistics and estimates, best answers the question of how much and where OR should be available in the EPS, given the uncertainties in the production of electricity from RESs in MGs and the uncertainties of their electrical load. The question of the OR in the EPS was investigated by Bayesian statistics, which links the simultaneous occurrence of a random variable (available electricity generation of RESs in MGs) with a statistical variable (electrical load power in MGs). The result of the proposed algorithm is the probability of the deficit or surplus of available energy in the form of active and reactive electric power in MGs, and the consequence of this probability is the probability of the need and degree of engagement of the OR using NRES (thermal and hydroelectric power stations). The algorithm is in simulation applied to the system of BH, and its implementation in daily system management is the subject of future work.

Keywords: Active Electric Power; Bayesian Probability; Microgrids; Operational Reserve; Reactive Electric Power.

Nomenclature

BH	Bosnia and Herzegovina
EPS	Electric Power System
MG	Microgrid
NRES	Non-Renewable Energy Sources
OR	Operational Reserve
ORRP	Operational reserve given Reactive Power
PPP	Photovoltaic Electric Power Plant
RES	Renewable Energy Sources
SHPP	Small Hydro Electric Power Plant
WPP	Wind Electric Power Plant

1. Introduction

The reliable operation of the EPS is possible if the adequacy and security aspects of the system are satisfied. With an OR in active and reactive electric power, the reliability of the EPS is ensured. For the OR to help ensure the EPS's reliability, it must have the necessary capacity and is well deployed within the EPS. The OR was only considered from a technical and technological point of view before introducing the electricity market. However, since the introduction of the electric power market, the OR has also started to be seen from an economic point of view. Also, by introducing new technologies of electric generator control (better *P*-*f* and *Q*-*V* regulation) and system control as a whole (SCADA systems), the answers to the questions of OR are complicated. With the emergence of distributed electricity production based on RES and the concept of MGs, the settings related to the OR are even more complex. Therefore, the definition and content of the OR vary between different electricity markets and energy groups.

In the rough division, the OR in terms of active electric power is divided, according to the IEEE and CIGRE working groups [1-4], into primary, secondary and tertiary (taking into account the crucial aspect of the reserve, which is the inertia of synchronized synchronous machines (thermal and hydro)). The OR in the form of reactive electric power can be divided in the same way, treating local voltage conditions as primary regulation, regional issues of voltage conditions as secondary regulation, and coordinated resource planning in reactive electric power at the level of

How to cite this article:
S. S. Halilčević, "Micrograms and the stability of electric power systems – the case of Bosnia and Herzegovina," *International Journal of Reliability, Risk and Safety: Theory and Application*, vol. 7, no. 2, pp. 116-132, 2024, doi: 10.22034/IJRRS.2024.7.2.11.

the entire EPS, based on technical-economic topics, can be treated as tertiary regulation of reactive electric power. One of the most significant associations in the world regarding the reliability of EPS is NERC (North American Electric Reliability Corporation). According to the NERC, there is a need for the market aspect of the OR to evolve and correspond as closely as possible to the actual situation of continuous changes in the EPS. This organization is continuously working to adapt the already adopted OR categories to the new experiences, knowledge, and circumstances of the EPS operation, especially those related to the ever-increasing infiltration of the RES into the structure of the EPS. In any case, it all boils down to the appropriate response of the EPS to changes in frequency and voltage and the need to fulfill the balance in active and reactive electric power throughout the EPS. Instruments with which the EPS response to these changes can be achieved are based on synchronous generators already synchronized on the network and those in reserve, then other devices such as dynamic and static sources of reactive electric power (to ensure the balance of reactive electric power in the system) and operational procedures based on relay protection. Without all these instruments and measures, it is impossible to ensure a reliable EPS.

Based on NERC recommendations, individual market energy basins (regional markets) define in their specific way the categories and needs for the OR (notably in the North American market) [5]. ERCOT (Electric Reliability Council of Texas) bases its OR on active power (ORAP) according to the demand for power [6]. The ERCOT system includes the capability of synchronous generation to maintain an electric power factor in the range of ±0.95, automatic voltage regulators in voltage control, and automatic operation mode. Wind power generation resources must be able to produce a defined amount of reactive electric power to maintain an established voltage profile. Generators based on RES are required to respond adequately to disturbances in the system (especially to situations characterized by low voltage in the environment of RES generators) through the system's so-called fault ride-through (FRT). FRT codes are mainly focused on generators and the voltage level to which they are connected (as they are required to follow network code-based standards) and are country-specific.

The Midcontinent Independent System Operator (MISO) includes under its ORAP the Regulating Reserve, Spinning Reserve, Supplemental Reserve, and related power response generator (MW/min), upward and downward (up Ramp Capability and Down Ramp Capability) [7]. The MISO concept in OR because of reactive power support (ORRP) aims to ensure efficient and reliable system operations through detailed evaluations and assessments performed for various system conditions, from real-time operations to the long-term planning horizon covering the next 10 years. Analyses typically include steady-state contingency analyses, transient stability/dynamics analyses, transfer studies, *PV/QV* analyses, static/dynamic real-time reactive electric power reserves calculations, generator interconnection and deliverability analyses. ORAP is recognized by the New York Region Independent Operator (NYISO) as an Ancillary Service that includes frequency control and response services, a service to achieve energy balance and a service to start the generator after the disintegration of the power system [8]. The NYISO may request corrective actions from voltage support facilities that are already in service, and available procedures for real-time voltage control are covered in the NYISO Emergency Operations, Transmission, and Dispatching Operations Manuals [9]. The Florida Coordination Council (SERC) [10] and the Southeastern Electric Reliability Council (SERC) presented sources of variable generator output to ensure reliable and secure interconnection operations of the EPS in Florida and 16 states of the Southeastern and Central United States. Both power pools use the guidelines in [11] concerning the provision of voltage support for electric power systems. Western Electricity Coordinating Council, PJM Interconnection [12], ISO-New England and Southwest Power Pool are developing their OR needs based on the recommendations of NERC and their own experiences.

The European Union Agency for the Cooperation of Energy Regulators (ACER) was established in March 2011 by the legislation of the Third Energy Package as an independent body to foster the integration and completion of the European internal energy market, electricity and natural gas markets. Among other numerous tasks, the Agency highlights the importance of introducing EPS nationally in all EU member states [13-14]. ENTSO-E, the European Network of Transmission System Operators for Electricity, represents 42 transmission system operators from 35 European countries. ENTSO-E was registered in European law in 2009 and has been in legal power since then. The OR is defined by ENTSO-E [15] as part of 'ancillary services.' Ancillary services relate to several functions that EPS operators contract with electric power plants and other participants in the EPS operation to ensure the system's security. This includes the capability to independently start a generator without an external voltage (the voltage from the EPS), frequency response (to maintain the system frequency with automatic and high-speed controllers), fast backup (which can provide additional electric power when needed on already synchronized or fast-start generators), the provision of reactive electric power services and various other services. In this context, ENTSO-E countries classify their OR into the following categories:

FCR - Frequency containment reserve and is also known as primary reserve (frequency control rapid automatic response; 30-second response);

A FRR - Automatic frequency restoration reserve and electric power control of the interchange between EPSs (automatic, 15-minute response) (it is also known as secondary frequency control);

mFRR - Manual frequency restoration reserves and electric power interchange control between EPSs (manual activation, 15-minute response) (it is also known as tertiary frequency control);

RR - replacement reserve (manual activation, response longer than 15 minutes).

In the context of providing sufficient reserve in reactive electric power, all countries and regions develop their common concepts of managing reactive electrical energy, as, for example, recommended by NERC [16]. ENTSO-E also works on identifying power system needs for dynamic and steady-state voltage aspects, grid security, and minimizing losses, with particular attention to transmission/distribution infrastructure interfaces [17]. New interconnection requirements for utility-connected photovoltaic and wind-based electric power plants are coming into force in several European countries, equipped to support grid operation and stability. Distributed generators must contribute to voltage stabilization to avoid disconnecting during voltage drops [18].

The concept of imbalance netting was also introduced by ENTSO-E [19-20]. This is the agreement between two or more regulatory areas to avoid simultaneous action on the change of frequency in opposite directions (since the result of such action is the return of the EPS to the starting point of the imbalance and represents a significant threat to the integrity of the EPS). International Grid Control Cooperation (IGCC) was established between 24 TSOs in the EU to better manage the automatic activation of the OR in frequency restoration.

The successful response of the OR to electrical imbalances in the EPS is influenced by several factors, such as the availability of wind and solar energy, changes in electrical load, the condition of the transmission network, and interconnection with neighboring systems and generators involved in the provision of reserves. In this type of analysis, it is essential to include the weather forecast, the price of electricity and system services, and the world's economic situation. These factors affect the OR differently, with a greater or lesser deviation from what is planned.

Otherwise, the issues of OR are open even at the beginning of the use of electricity and the formation of electric power systems. OR was not called and treated as it is today. Still, the issue of compensating or reducing electricity production when there is a shortage or surplus of electricity has always been open. In addition, academia has been researching to find answers to the question of the necessary OR. Different algorithms are used: deterministic, probabilistic, and simulation, as well as different mathematical tools, from algebra to artificial intelligence.

In the academic sense of the word, about the methods of determining the OR, one of the first articles was in [21], followed by a series of publications on the subject, [22], [23], up to research evaluating the impact of RES on the OR, as given in [24-27], up to the research presented in [28]. All the mentioned academic works offer solutions for calculating the OR that have certain disadvantages and advantages each other. Those based on deterministic approaches do not respond to the stochastic nature of EPS operation; others that use statistical and probabilistic methods are exposed to greater or lesser statistical error. Some use a general probabilistic representation and inference mechanism for arbitrary nonlinear time-dependent domains, such as Bayesian statistics in various forms. For example, in the article in [29], using the Dynamic Bayesian Belief Network, a reserve forecast is based on the loss of the largest power generator unit. Also, the users of this dynamic Bayesian network do not provide an answer to the spatial distribution of the required OR, that is, whether the calculated required OR can be realized in the EPS due to congestion in the transmission part of the EPS. Finally, various forms of artificial intelligence are used to calculate the required OR, such as machine learning based on neural networks, and an article on the subject is given in [30]. The neural network model presented in that manuscript uses 34 inputs and four variables in the neural network's output: forecast errors of net demand, demand, solar and wind availability. The spatial component of the OR is again not the focus of researchers.

The [31] illustrates the process of determining the OR based on the following:

- Renewable uncertainty is modeled on scenarios.
- Safety restrictions shall ensure safety concerning unit failures.
- The resulting optimization model is traceable and does not need degradation.

The presented procedure was assessed as practical based on determining the OR as a percentage of EPS load.

U [32], the OR demand determination method considering the different periods of uncertainty of wind and solar is presented to meet the reserve demand of new power systems with high penetration of solar and wind energy. The authors have gathered the load, wind, and solar forecast data of one of the provinces in China in 2020. The prediction errors of load, wind power and photovoltaic have been obtained by differentiating them respectively, and the total prediction error is obtained by adding the three. However, the results obtained are not operational.

In [33], the authors analyzed the long-term impact of solar and wind energy on the reliable operation of the EPS. The authors have suggested that ensuring the reliability of wind- and solar-based systems will require considerably more weather data in system planning than the current practice. However, when considering the potential costs associated with unmet electricity demand, fewer planning years may suffice to balance expenses against operational reliability.

Recent research, as in [34], shows hybrid systems mitigate energy intermittency and improve grid stability. In doing so, they emphasize using sophisticated electronic power sources to ensure the seamless integration of solar and wind energy. These devices can adjust real-time voltage and frequency parameters to provide a stable and reliable power supply. This has already been considered in this work with the inverters (see Fig. 11).

In this study, the required value of the OR for non-renewable electricity sources was determined based on statistical data on the load in certain parts of the system and the production of electricity from RES (and their probabilities of occurrence in the total ranges of changes). In this context, Bayesian probability is used because it is a conditional probability that works on the principle of cause and consequence. The presented procedure offers several options for the likelihood of the occurrence of a deficit or surplus in the production of electricity in MGs so that the method for determining the OR in the system is not automated but requires the participation of the system operator to choose the best one from the offered options. Due to the complexity of determining the necessary OR in the system, the protocols for its determination in the world are not uniform and unique. This research is motivated precisely by the fact that such an essential aspect of the operation of the EPS still does not lead to a single solution model, such as, for example, power flow models based on the methods of Newton–Raphson and Gauss-Seidel.

The layout of the individual sections of this article is as follows. Section 2 describes the identified uncertainties and difficulties in determining the operational reserve. In section 3, the calculation method is presented - the Bayesian theorem. In sub-sections 3.1 and 3.2, the Bayesian theorem used to calculate the OR in the form of active and reactive power is presented. Section 4 presents the results - Bayesian probability applied to the EPS of Bosnia and Herzegovina. Section 5 – Conclusion – presents the Bayesian approach's benefits and essential points about future activities in this field. Section 6, References - represents a list of articles this paper references.

2. Uncertainties and Difficulties in Determining the Operational Reserve

Today, more and more PPPs, WPPs, and SHPPs participate in electricity production within the EPS. The reasons are economic and ecological. Setting a 10 kW PPP on the roof of a family house or a wind farm on a land plot brings income to investors and reduces gas emissions caused by electricity production using fossil fuels. More such areas minimize air, soil, and water pollution throughout the country. Therefore, in BH, the construction of PPPs, WPPs and SHPPs was intensified (up to the ban on the construction of SHPPs, a lot of investment was made in this form of RES) thanks to the new motivating laws on RES in BH [30], based on laws in the EU [31]. Many small investors have already built or are negotiating with companies about installing RES equipment because the sale price of the produced kWh is handsome and provides people with regular monthly income, which is especially important in this time of recession and inflation.

However, this is one side of the medal, and the other side of the medal is the technical side, which the legislators themselves often forget: the operation of the EPS in conditions of relatively large and constantly growing infiltration of the RES into the EPS. Maintaining frequency and voltage as the essential task of preserving the integrity of EPS, along with the challenges of the market and economically efficient functioning of these systems, is a complex job for all people who plan and manage the EPS. In this context, the answer to the questions about power and energy reserves in the EPS is complex in the uncertainty surrounding RES.

Giving a more precise answer to this question will enable a reliable and cost-effective operation of the EPS, which will also support efforts to maximize RES penetration into the EPS in meeting the population's electricity and climate-change response needs.

RES are located in clusters (rounded spatial units) connected to the power grid by low, medium, or high-voltage electric power lines, Fig. 1.

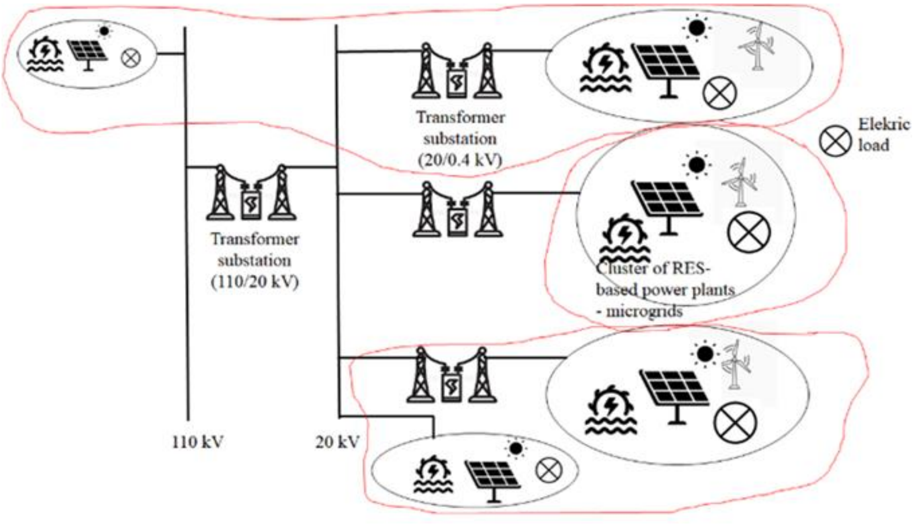


Figure 1. Clusters of RES-based electric power plants with communication and information infrastructure from MG

These clusters are known as MGs. The basic explanation of an MG considers electrical generators, electrical energy storage devices, controllable electrical loads, converter units, and communication links, all supported by information technology [35-37]. Given the MG topology, they can be divided into three main groups. AC, DC, and hybrid [38-39]. MG is a group of interconnected consumers and distributed power sources at different voltage levels, which act as a single unit that can be managed concerning the EPS. It may be connected and disconnected from the EPS to operate in an interconnected or islanded mode. MGs can improve the reliability of the electric power supply to electric power users and the resistance of the EPS to interference. Advanced MGs allow local means for electricity generation: PPP, WPP and SHPP, then power plants using biomass and local storage of generated electricity, all as a new aspect of flexibility of the operation of the EPS.

Regional distribution-level operators (Distribution System Operator (DSO)) must send the EPS operator information on electricity needs in the next 24 hours through electrical load diagrams created hourly. Now, the work of the DSO is becoming more complicated due to the increasing penetration of RES within the control area itself. Depending on the values of solar radiation, wind speed, and water inflow to SHPPs, its own RES can cover the electrical load within one distribution area, and sometimes it is only possible to a certain extent, so there is a continuous interaction of MG with the DSO and with the EPS operator.

This raises the question of how much electric power should be deployed in non-RES-based electric power plants (NRES) (based on fossil fuels, such as coal, natural gas and oil, and hydroelectric power plants above 10 MW) to cover the daily electrical load curve. Also, how much should the OR be balancing power according to the ENTSO-E to preserve the integrity of the EPS [40]. According to the EPRI classification of OR [41], this study aimed to regulate frequency and voltage in the context of electrical load variation and changes in RES availability. The estimate of the OR required in the context of generator and transmission line failure has not been the subject of this study, and there are many methods and algorithms in the literature to determine the OR in such cases.

The determination of the OR is a purely stochastic issue, as there are ambiguities on both sides: on the side of electricity production in RES and on the side of electricity consumption, Fig. 2.

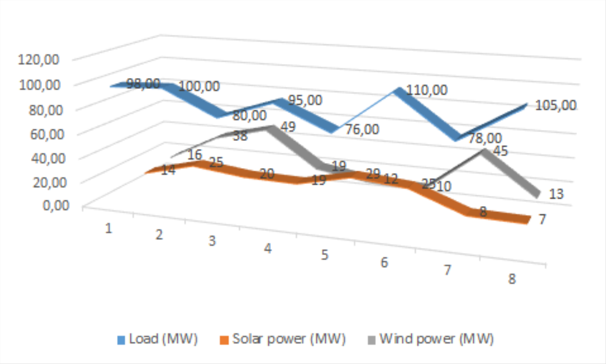


Figure 2. Changes in load, solar and wind energy in region 2 of BH EPS for the eight-hour time interval on 14 April 2023

Although numerous works in [42-44] (focusing mainly on the integration of wind farms) provide more or less precise answers to these challenges, the EPS operators still adhere to the rule based on the principle that the power of the OR equals the power of the largest power unit in the EPS. Or, somewhere, 1.5 times the power of the largest power unit. This is undoubtedly the most straightforward way, but the question is how much is justified from an economic and operational point of view.

To ensure the stability of the frequency of the EPS and more efficient determination of the needs for OR, an approach based on Bayesian probability was investigated. As OR determination methods vary from country to country and region to region, OR designation creates confusion and controversy with technical and economic implications. This is particularly evident in recent years, with the increasing introduction of RES in EPSs. This confusion and controversy stem from the stochastic nature of RES, electrical loads, electric power lines, and fossil fuel-based generators, so the stochastic approach must solve this problem. The need for OR in the power balancing function in the EPS, which has the task of "ironing out" the unpredictability of the relevant variables (in this case, RES and electrical load), must be based on probability. Numerous probabilistic models describe different phenomena, primarily models based on parametric and nonparametric statistics, then different probabilistic distributions (density functions) and several models for estimating different statistical variables. The statistics mentioned refer to objective probabilities. However, in the multilayered and multidimensional assessment of the required OR, it is necessary to have other available information that may appear to be pertinent in addition to information about the issues and scenarios.

In this sense, the Bayesian method of estimation shows features that combine classical statistics based on samples, using which the necessary statistical variables were obtained (means, intervals of variable change with a certain statistical confidence of the estimation of those intervals) and estimation of the value of the variables in the future. Thus, Bayesian statistics connect the past and future to make better decisions today. Such a tool is suitable for all those who make decisions in any area of life, even when calculating the necessary OR within EPS.

Taking into account the mentioned features of the OR calculation models and algorithms mentioned in this and the previous chapter, the novelty of the paper and contributions of this research are reflected in the following:

- The research results refer to the calculation of surpluses/deficits of electric power in MGs, using Bayesian probability, based on which the decrease/increase of OR "stored" in power plants that use non-renewable energy sources (and hydroelectric power plants above 10 MW) is calculated;
- Calculating electric power surplus/deficit for each identified MGs explicitly shows which conventional electric power plant (or several conventional electric power plants) should be with its OR the support for each of the MGs individually. This makes it impossible to engage electrical power plants that are electrically (and geographically) distant from the place where the OR is needed, which minimizes the probability of electric power transmission line congestion,
- The research results refer to the stochastics of wind, solar, and water energy forms and the stochastics of electrical loading in the analyzed MG. The reserve calculation for the failure of a conventional power station is left to national operators who, as mentioned in the previous chapter, solve the problem in their way. The research presented in this article does not touch on that part of the OR calculation. Still, the proposed model based on Bayesian probability is added to the existing OR calculation practices valid in certain national EPS, which only refer to conventional electric power plants (coal, gas, oil, and large hydro).

3. Method - Bayes' theorem

The application of Bayes' theorem originated from a constantly changing and uncertain world around us. The current estimate of the probability of an event occurring has already changed at the next time point. In addition, several variables interconnected by stronger or weaker mutual influence accompany the uncertainty of events. Bayes' theory can be found in many areas of different scientific and professional fields, among them in EPS operations. Most of Bayes' applications in the field of electric power systems are found in reliability and stability assessment, EPS dynamics [45-47], forecasting [48-49], fault estimation [50], parameter estimation [51], and probabilistic power flow analysis [52]. Bayes' concept of probability is based on modified previous experience, the confirmed probability of an event (a priori probability), considering new information and forecasts related to those events to calculate the a posteriori probability [53]. It can be said that the a posteriori probability is an updated previous (a priori) probability. Bayes' likelihood is based on how likely an event or phenomenon is to occur (hence the term likelihood function). A posteriori probability updates this likelihood function, Fig. 3, to expand the acquired knowledge of the probability of an event according to new information (knowledge).

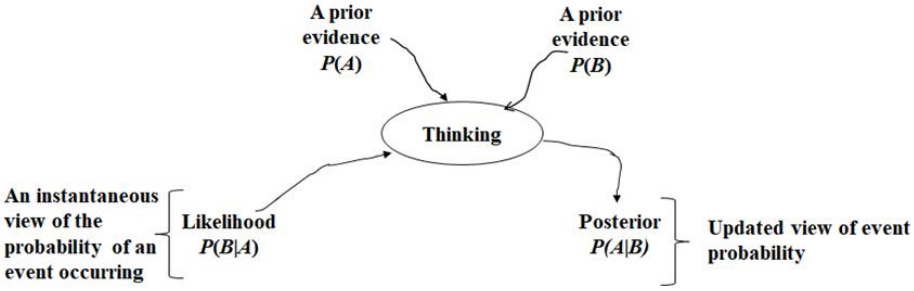


Figure 3. Bayesian probability concept

Bayesian probability is a conditional probability. The mathematical definition of conditional probability is as follows:

$$P(A \mid B) = \frac{P(A \cap B)}{P(B)} \tag{1}$$

Followed by the Bayesian rule:

$$P(A \mid B) = \frac{P(B|A) \cdot P(A)}{P(B)} \tag{2}$$

3.1 Bayes theorem applied for the calculation of OR in the form of active electric power

In OR, *P(A)* and *P(B)* are the probabilities of the forecasted electrical load and the RES-based electric power in the same MG. The likelihood of occurrence of a particular electrical load *P(A)* in one MG is based on the relative electrical load frequencies measured for four seasons, working and non-working days, and each hour of the day. So, knowing what the season is, whether it is a working or a non-working day, and for what hour the calculation of that day is, it is known which relative frequency histogram should be chosen for the calculation of OR. The histogram is described with probabilities of occurrence of certain electrical load classes (the entire electrical load spectrum in MG is divided into classes at appropriate intervals; the width of these intervals ranges from 5 to 15 MW and is different for each MG individually). The MG electrical load database is continuously updated (the results of calculation of power flows in the networks of Electro-distribution Tuzla and other electric distribution companies in Bosnia and Herzegovina can be obtained on request (for the year 2023). Figure 4 shows the probability density of load on 14 April 2023 for the MG of northeastern BH (region 2, in Fig. 8). In the calculation of the probability of surplus or deficit of energy for a particular hour of that region, the load of that region with the highest probability is taken into consideration.

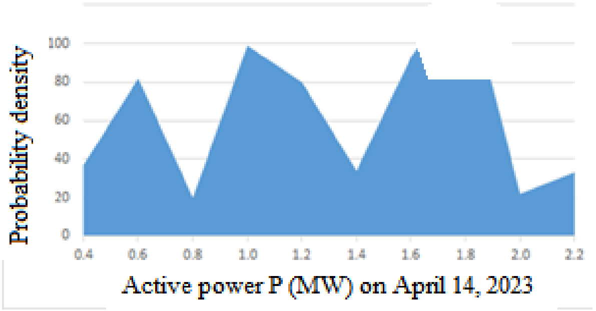


Figure 4. The probability density of electrical loads on 14 April 2023 for the microgrid of northeastern Bosnia and Herzegovina (region 2, in Figure 8)

The probability of the electricity production from RES *P(B)* in the MG considered is calculated based on the hour-ahead weather forecast. The available power from PPP, WPP, and SHPP is estimated from the weather forecast in several probability categories (in our case, in three probability categories: high, medium, and low probability). These probabilities of available electric power in MG are based on the probabilities (high, medium and low probability) of occurrence of solar radiation (MJ/m^2), wind speed (m/s) and water inflow (m^3/s). In this way, using individual statistical distributions (parametric, nonparametric, and distribution parameter estimation methods) is avoided, especially those in wind speed estimation, which are unnecessary for this type of analysis. Here, we use data close to real-time (an hour before the actual occurrence of electrical load power and electricity production in RES-based electric power plants).

Figure 5 shows the probability density of power from RES on 14 April 2023 for the MG of northeastern Bosnia (region 2, in Figure 8). In the calculation of the probability of surplus or deficit of energy for a particular hour of that region, the first three highest power probabilities from RES (high, medium and low probability) are taken into account (the data can be found on the website of the author of this article: https://www.researchgate.net/lab/Suad-S-Halilcevic-Lab).

The selection of the probability of the occurrence of a specific value of surplus/deficit of active electric power in the considered MG (likelihood $P(B|A)_{\Delta^+}$ i $P(B|A)_{\Delta^-}$), is based on individual data for each hour for the last three years. Each surplus/deficit is placed in a histogram labeled in individual width classes from 1 MW to 5 MW, depending on the RES potential and electrical load power in individual MGs. The surplus/deficit active electric power histograms for the 4567th hour in a year for one of the MGs in BH are shown in Fig. 6. The first three highest probabilities refer to surplus active electric power of 5.0, 4.0, and 6.0 MW with probabilities of 25%, 22%, and 20%, respectively. The highest probability of an active electric power deficit for a given hour and in a given MG is 11%, with an active electric power deficit of 20 MW. As the first three highest probabilities are considered, this active electric power deficit is not considered when calculating the posterior probability of active electric power surplus/deficit in the considered MG.

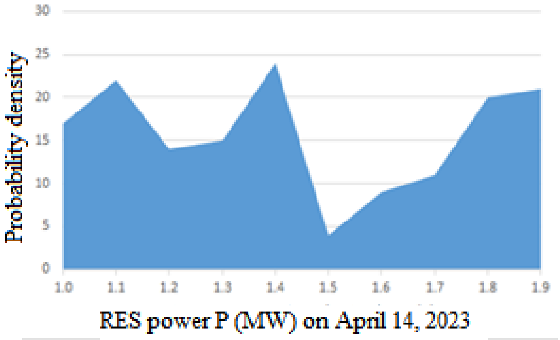


Figure 5. The probability density of power from RES on 14 April 2023 for the MG of northeastern Bosnia and Herzegovina (region 2, in Figure 8)

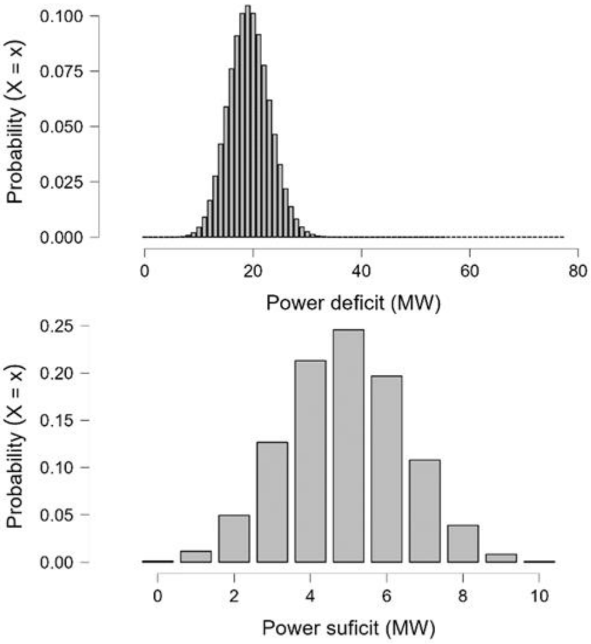


Figure 6. Two histograms describing the distribution of active electric power deficits and surpluses in the considered MG for the 4567th hour of the year (a priori probabilities, which in the next step are corrected with *P(A)* and *P(B)* to obtain the posterior probabilities of the occurrence of deficits and surpluses of active electric power in MG, $P(A|B)_{\Delta^+}$ i $P(A|B)_{\Delta^-}$

It is possible to analyze the ordinary state of the available capacity of RES and the electrical load in all MGs, but this is possible only when the state of switches (switched off or on) in the substations is known. Through the ring form of the grid is created, through which the export of electricity from one MG to another can be realized and vice versa. Only DSOs know this information, and the situation varies daily. This study considered individual MG states with their own production and electricity consumption.

Thus, the probability $P(A|B)$ represents the posterior probability of electric power deficit/surplus derived from the expected probability $P(B|A)$ of electric power deficit/surplus (based on the recorded data in the past five years). $P(A)$ and $P(B)$ are the probabilities of the occurrence of electric load and electricity produced from RES in the same hour and the same MG. The probability of $P(A|B)_{\Delta^+}$ represents the surplus in active electric power (the positive difference Δ^+ between the available RES power and the electrical load) in the MG under consideration. The second relates to the $P(A|B)_{\Delta^-}$ and represents the deficit in active electric power (the negative difference Δ^- between the available RES-based electric power and the electrical load) in the MG under consideration:

$$P(A|B)_{\Delta^+} = \frac{P(B|A)_{\Delta^+} \cdot P(A)}{P(B)} \quad (3)$$

$$P(A|B)_{\Delta^-} = \frac{P(B|A)_{\Delta^-} \cdot P(A)}{P(B)} \quad (4)$$

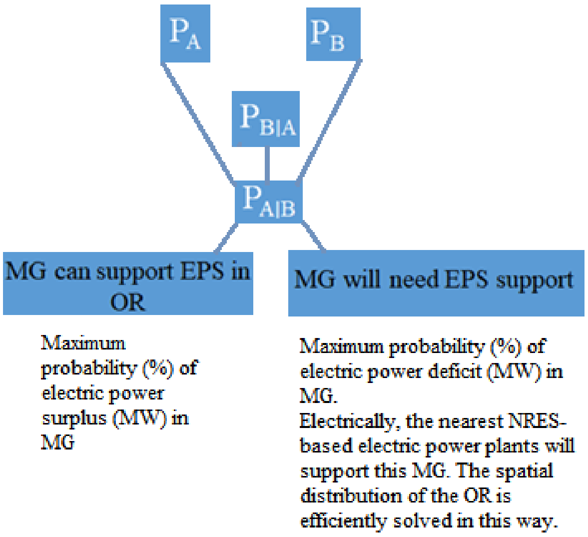


Figure 7. Procedure for calculating the required OR in the EPS based on Bayesian probability

These calculated probabilities show, in the first case (3), the probability of a reduced need for OR in EPS (energy surplus in MG Δ^+), and in the second case (4), the probability of an increased need for NRES as OR in the considered EPS (energy deficit Δ^- in MG).

The procedure for calculating the probability of an OR in the context of an energy surplus or deficit in MG is shown in Fig. 7. The operator of MG is assumed to report to the EPS operator a plan by which the energy exchange with the EPS is zero, so that all active electric power injections from or in MG are covered by activating the OR downward or upward, i.e., by changing the NRES active electric power output.

The MATLAB toolbox (the MATLAB scripts) for Bayesian functional data analysis, which implements a hierarchical Bayesian model for smoothing multiple functional data under the assumptions of the same underlying Gaussian process distribution, was used to calculate $P(A|B)_{\Delta+}$ and $P(A|B)_{\Delta-}$, [54].

3.2 Bayes theorem applied for the calculation of OR in the form of reactive electric power

The calculation of the OR in the form of reactive electric power is based on the fact that it is most economical to provide reactive energy locally to avoid significant energy losses and large voltage deviations. Also, the transport of reactive electric power is limited by the limited capacity of the transmission part of the EPS and the length of its transmission lines. The state of the connection points between the distribution and transmission parts of the EPS is of great importance. All connected MGs must maintain the power factor at 0.95 to 1.0 (capacitive and inductive mode) at the interconnection points with the distribution or transmission network. MGs connected to the transmission segment of the EPS with a voltage of 110 kV and above are necessarily involved in voltage regulation and servicing of the EPS in terms of reactive electric power.

In the context of the OR in terms of reactive electric power, $P(A)$ and $P(B)$ are the current records on the probability of demand for reactive electric power in MG and the available reactive electric power (energy) of the RES in the same MG.

The probability of a specific reactive electrical load $P(A)$ in one MG is defined similarly for the active electrical load. The likelihood of the available reactive electric power in the RES depends on their engagement by active electric power. The probability presented in (1) sublimates the probabilities $P(A)$ and $P(B)$ that occur simultaneously and that a priori make up the probability of the occurrence of a surplus or deficit of reactive electric power in a given MG.

When these probabilities, $P(A)$ and $P(B)$, are updated with new data for the next hour of calculating the state of reactive electric power in MG, the following is a posterior probability of surplus or deficit of reactive electric power in the considered MG. The $P(A|B)$ is calculated for two probability categories $P(B|A)$: the first one for the surplus of reactive electric power (energy) (the positive difference $\Delta+$ between the available reactive electric power of RES and the reactive electrical load in the same hour and the same MG). The second one is for the deficit (shortage) of the reactive electric power (the negative difference $\Delta-$ between the available reactive electric power of RES and the reactive electrical load for the same hour and the same MG).

The OR required in terms of the reactive electric power contained in the RES is critical regarding the RES behavior in the case of the Low-Voltage Ride-Through capability. Different countries in this context define and seek different modes of operation of PPP and WPP to successfully contribute to the maintenance of voltage profiles at the desired values in case of short circuits and other disturbances in the system. The inverter built into PPP and WPP can provide reactive electric power at full installed capacity. So, suppose solar insolation decreases so that active electric power generation is not 100%, but 10% of the installed capacity of the PPP. In that case, the converter can use 90% of its remaining capacity to supply reactive electric power and improve the quality of the operation of the utility network [55].

In most European countries, the required power factor for consumers and producers of electricity is between 0.95 and 1.0, which implies demand or production for Q in the amount of 0.33 kVAr per kW of active power. Thus, RESs produce reactive electric power in MG that provides the required cosφ=0.95 and is equal to $Q' = \frac{1}{3}P'$, where P' is the active electric power with the highest probability, according to the Bayes theorem, which is what MG can produce. Suppose this power P' is less than the rated electric power of a particular RES-based electric power plant. In that case, a reserve in apparent (total) power can be used for reactive power needs out of the ±0.95 power factor range. In this context, MG can be the producer or consumer of the reactive electric power Q (energy) depending on the voltage conditions in the EPS distribution and transmission network:

a) $Q>Q'$, which implies the injection of reactive electric power from MG into EPS in the amount of $\Delta Q= Q-Q,'$

b) $Q=Q'$, implying the balance achieved in reactive electric power in the MG considered,

c) $Q<Q'$, which implies reactive electrical energy consumption, that is, the import of reactive electrical energy from EPS into the considered MG in the amount of $\Delta Q=Q-Q.'$

The availability of reactive electrical energy in all MGs in EPS is calculated as the sum of all ΔQ, where a positive sign score indicates the injection of the reactive electric power from MG to EPS, and a negative sign score suggests the capture of reactive electrical energy from EPS to MG.

Based on the above, the problem of excessive amount of reactive electric power generated by high voltage lines (110, 220 and 400 kV) in BH EPS and causing long-term elevated voltages in that part of the system could be solved by engaging MG, connected to 110 kV voltage and above, in inductive mode. The amount of reactive electric power that could be "withdrawn" from the system into the MG depends on the technical-technological characteristics of electric power plants based on RES in MG and the Grid Code and set conditions for connecting electric power plants based on RES in EPS. The Independent System Operator of BH through the Grid Code [56] requires that the MG connected to the transmission network (110 kV and higher) have a power factor in the range of 0.9 to 1.0 (for the delivery and consumption of reactive power). In necessary cases, other power factor values are also possible due to the technical-economic benefit agreed with the RES-based power plant's owner and the EPS's operator [57].

3.3 Results - Bayesian probability applied to the electric power system of Bosnia and Herzegovina

The proposed algorithm for determining the OR in the form of active and reactive electric power has been used in the BH EPS example, Fig. 8. The total installed capacity of the RES in BH EPS (the capacity from 2023) consists of 57 MW in PPP, 200 MW in WPP and 176 MW in SHPP (small hydroelectric power plants with installed power from 0.5 MW to 10 MW were considered).

The BH electric power market has a balance mechanism to manage imbalance situations. In this mechanism, the balancing parties purchase and/or sell the balancing electrical energy based on instructions from the Independent System Operator (ISO) to maintain the system balanced between production and consumption in real-time, considering net cross-border exchange. All electricity suppliers with a generation power capacity greater than 0.5 MW must participate in Balanced Responsible Parties (BRP). BRP is a licensed party that has assumed balance responsibility for the balance group and, as such, is registered with the BH ISO. BRP informs ISO BH about the production diagram for the individual hours of the day ahead. After that day, the ISO records the measured situation (imported and exported electric power). It transfers the financial obligation and responsibility following the participation of individual BRPs in maintaining the balance of electric power (and energy) in the EPS. Within its group, the BRP identifies balance-responsible members within which mutual financial obligations are regulated. Each member of the balancing group has a balance agreement with BRP, and BRP has a balance agreement with ISO, all based on the concept of auxiliary services for balancing EPS of BH, which was made by the State Electricity Regulatory Commission (SERC).

Data on the probability of the expected active electric power deficit/surplus in MG4 and a priori data on the probability of available active electric power in RES and the probability of electrical load for the same hour in a given MG4 are presented in Table 1. Based on the input data shown in Table 1 and using equations (3) and (4), the probabilities of the required OR (upward or downward) are calculated according to the hourly forecast of electric power generation in RES and electric power demand in the given MG4, Table 2.

The maximum probabilities results in Table 2 are underlined and bold (data refer to the southern part of the BH EPS). The maximum probability of deficit in the amount of 8 MW is 63%, and the maximum probability of surplus active electric power in the considered MG4 for a given hour (shown for 3894th hour of 8760 hours in 2023) in the amounts of 12 MW and 17 MW are 68% and 62%, respectively. In this case, the system operator is unenviable because the probabilities of deficit and surplus are close. Therefore, its decision is risky in the context of which probabilities should be selected in the calculation of the OR for the next hour of operation of the BH EPS concerning the energy situation in MG4 (south part of the BH EPS).

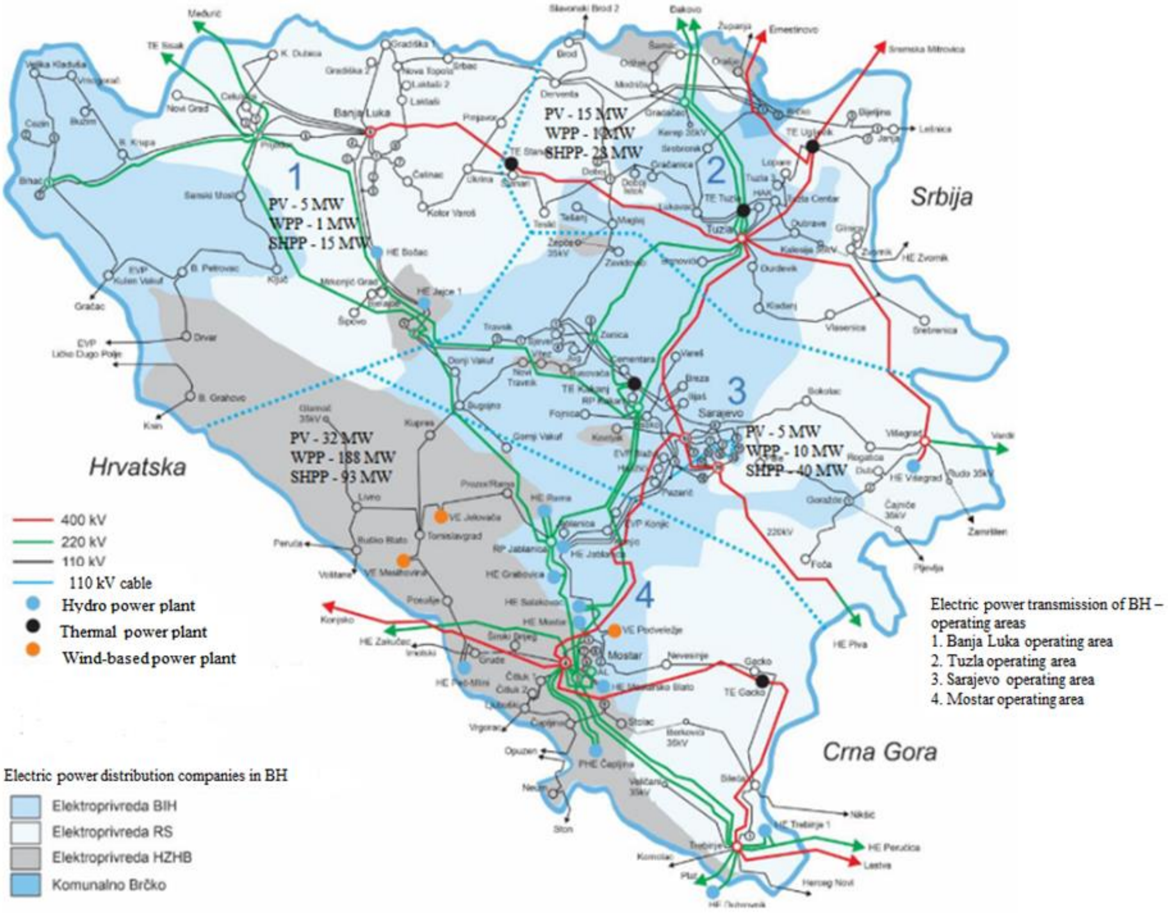
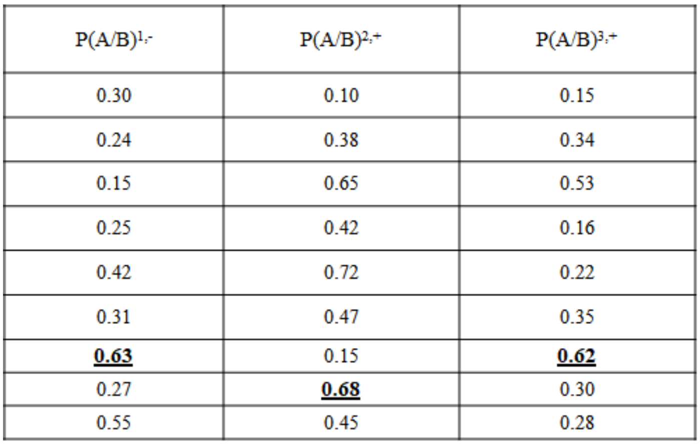


Figure 8. EPS of BH is divided into four parts with its own MGs and electrical loads

Table 1. Probabilities related to MG4 for the calculation of the required OR in EPS based on the Bayesian probability

$P(B\mid A)$ (%); a posteriori probability of suficit/deficit of active electric power in MG$_i$ (they are presented as a probability distribution (probability density); Each probability carries a deficit or surplus quantity	A priori probabilities		
	Probability of electrical load in MG$_i$, $P(A)$ (%)	Probability of available active electric power of RES in MG$_i$, $P(B)$ (%)	$P(A\mid B)$ (%); the probability of suficit/deficit of active electric power in MG$_i$ obtained from the recorded data in the last five years
$P^{1,-}_{(A\mid B)}$	$P^{1}_{(A)}$	$P^{1}_{(B)}$	$P^{1,-}_{(B\mid A)}$
$P^{2,+}_{(A\mid B)}$	$P^{2}_{(A)}$	$P^{2}_{(B)}$	$P^{2,+}_{(B\mid A)}$
$P^{3,+}_{(A\mid B)}$	$P^{3}_{(A)}$	$P^{3}_{(B)}$	$P^{3,+}_{(B\mid A)}$

Table 2. Results of the calculation of the probability of the occurrence of a deficit or surplus of active electric power (energy) in MG4 (sign minus represents the deficit (MW) and sign plus represents the surplus (MW)). In this case, we have two probabilities for the surplus of active electric power



$P(A/B)^{1,-}$	$P(A/B)^{2,+}$	$P(A/B)^{3,+}$
0.30	0.10	0.15
0.24	0.38	0.34
0.15	0.65	0.53
0.25	0.42	0.16
0.42	0.72	0.22
0.31	0.47	0.35
0.63	0.15	**0.62**
0.27	**0.68**	0.30
0.55	0.45	0.28

Following the event selection rules (deficit or surplus of electricity) with the highest probability, ISO will select the event with the highest probability (in this case, the highest probability is 68%) when calculating the required OR, referring to the surplus electricity in MG4 of 12 MW, and will accordingly reduce the OR requirements for the NRES generator.

This calculation was made for the remaining three MGs in the BH EPS (Fig. 8). The sum of the deficits/surpluses with the highest probabilities in all MGs gives the quantity of OR required in non-renewable energy sources with the highest probability of appearance.

The OR needs (balancing energy of centralized automatic secondary and tertiary regulation) recorded in 2023 in the BH EPS [56] are shown in Fig. 9.

The needs assessment for OR in BH EPS is based on the application of Bayesian probability, which takes into account the uncertainty of RES production and electrical load uncertainty in MGs of given EPS, as shown in Fig. 10.

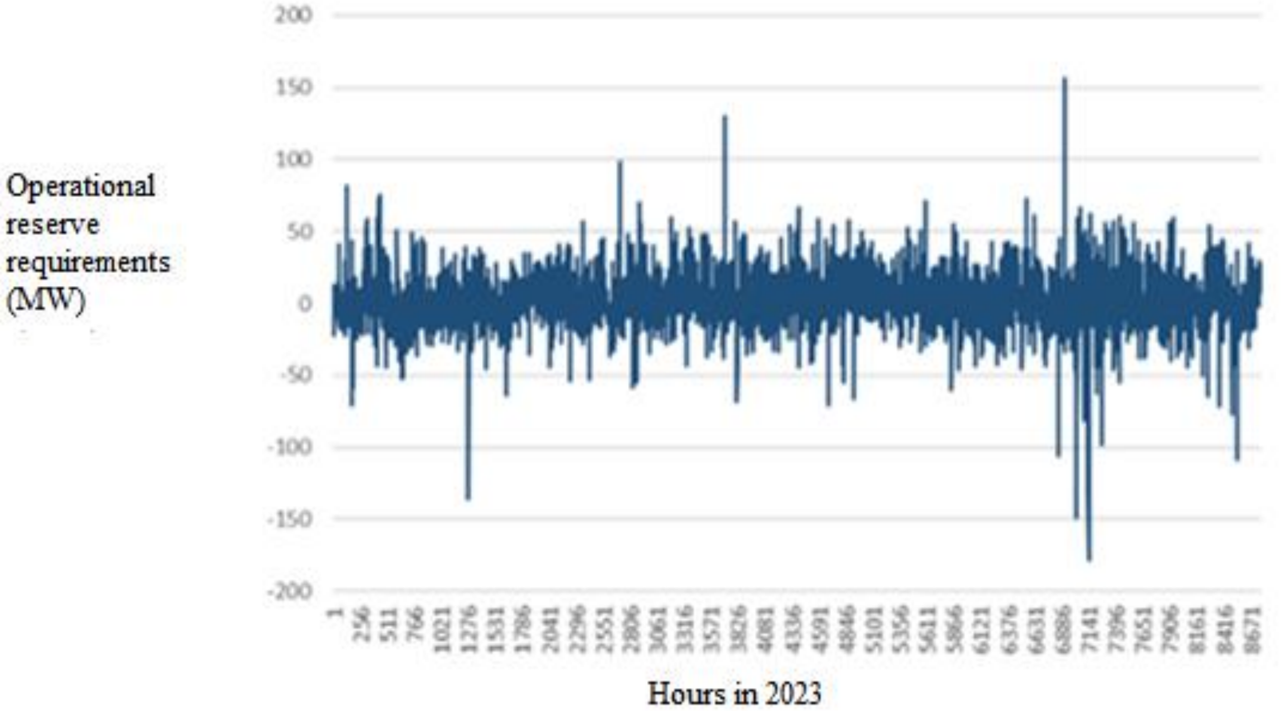


Figure 9. OR needs in the BH EPS in 2023 (source: ISO of BH)

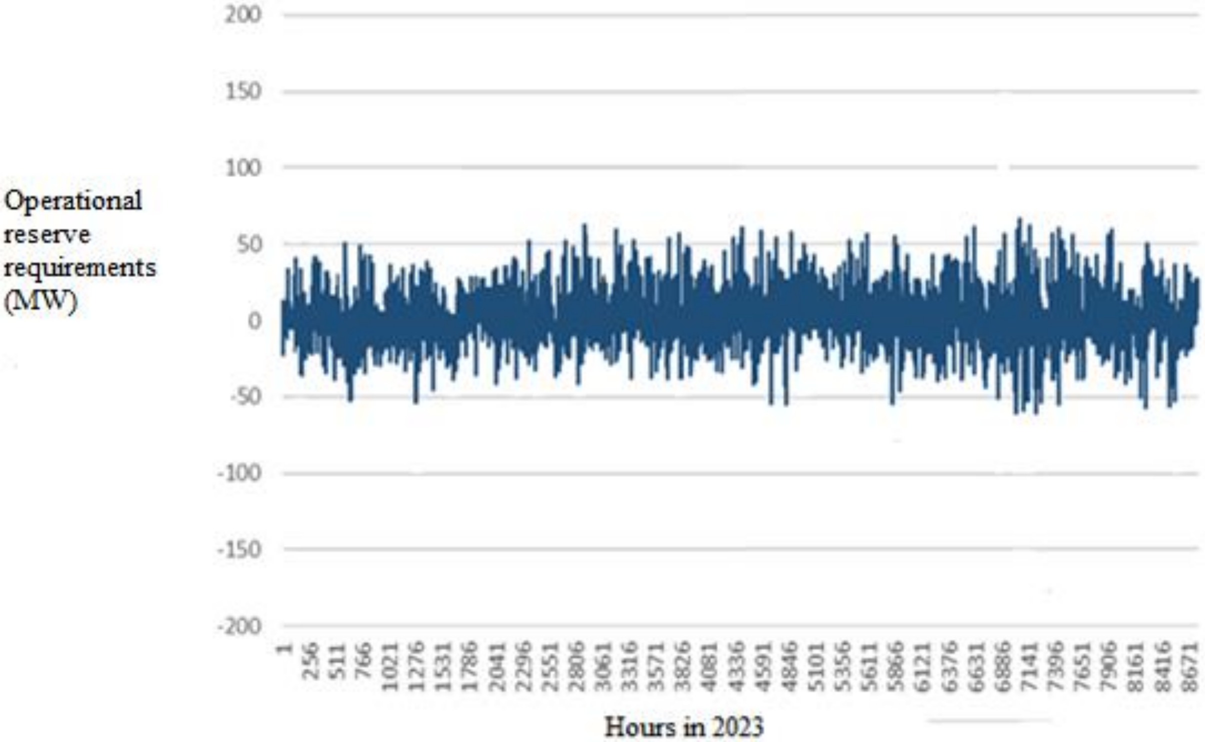


Figure 10. OR needs in BH EPS in 2023 estimated using Bayesian probability

Statistical data on OR (MW) needs for 2023 in BH EPS are given in Table 3. The data in the second column are based on the current practice of the BH EPS according to ENTSO-E rules. These rules apply to the OR, which maintains the nominal value of the frequency so that sufficient OR is held to deal with incidents occurring within a given control synchronous area.

The dimension of the incident is defined as the maximum expected instantaneous power deviation between production and consumption in the control area. In the future, the development of MG will have to be considered when determining the magnitude (dimension) of the incident. The algorithm for calculating the OR in such circumstances is presented in this article and is based on an objectively calculated difference between electricity generation and consumption. The OR calculation results based on the presented algorithm are given in the third column of Table 3.

The values in Table 3 show that there has been a significant improvement in the reduction of the required (and mandatory) OR. Thus, 79.5% and 95.4% of the OR needs in 2023 are in the range of ±25 MW, without and with the application of the proposed algorithm based on Bayesian probability, respectively.

Table 3. The statistics of the OR (MW) needs in 2023

	No Bayesian probability (current practice of calculating the OR in the ISO of BH, under ENTSO-E rules)	With Bayesian probability (calculated OR taking into account RES uncertainties and electrical loads in MG)
Maximum value	156.7	69.4
Minimum value	-178.6	58.9
Mean value	2.9	1.7
Standard deviation	14.6	9.6

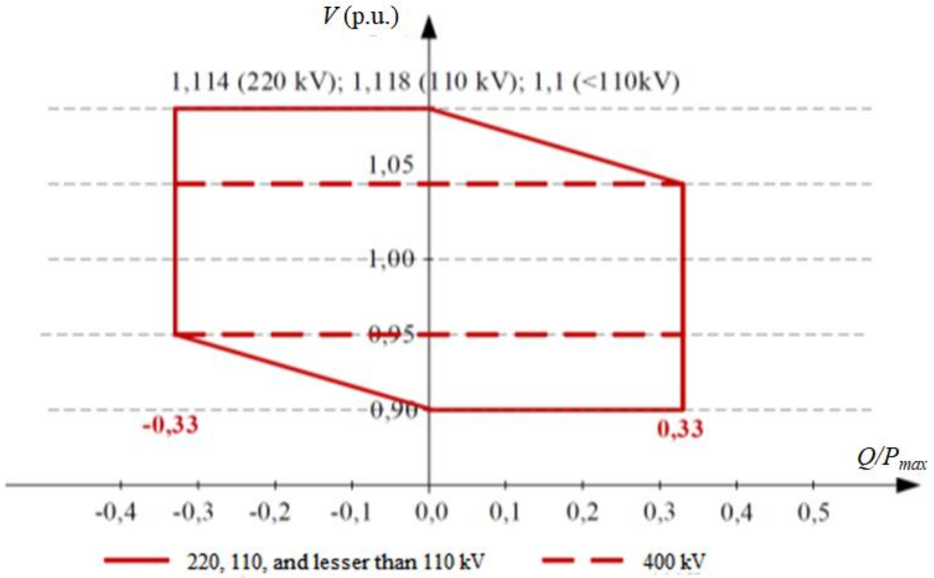


Figure 11. The characteristic of Q/P_{max}-V at the points of connection of MG to EPS according to the BH grid code

The reactive electric power in MGs is calculated based on the algorithm presented in 4.2. The influence of MGs is presented to solve the problem of long-term elevated voltages above the rated values (110, 220, and 400 kV) in BH EPS. The participation of MGs in the maintenance of voltages at their nominal values is considered the grid code in BH. The network code defines the Q/P_{max}-V characteristic that refers to the connection points of MGs in terms of voltage maintenance and the production/consumption of reactive electric power. The characteristic mentioned is given in Fig. 11. Four cases were analyzed: absence of participation of MG in the regulation of reactive electric power in EPS and with Participation with a power factor of 0.85, 075, and 0.65, inductive (consumption of reactive electric power) and capacitive (generation of reactive electric power). The influence of MG in the area marked with number 4 (as shown in Fig. 8), which includes the critical transformer substation Mostar (400/220/110 kV), was analyzed. The voltages on the bus of 110 kV within the observed transformer station, Fig. 12, were mainly within the allowed values, except for the 250th hour (without MG participation in reactive power control in this part of BH EPS). In addition, the same was found for the 222nd, 195th and 156th hour, with insufficient participation of MG in the regulation of reactive electric power in this part of the EPS, with power factors of 0.85, 0.75, and 0.65, respectively, in inductive and capacitive mode.

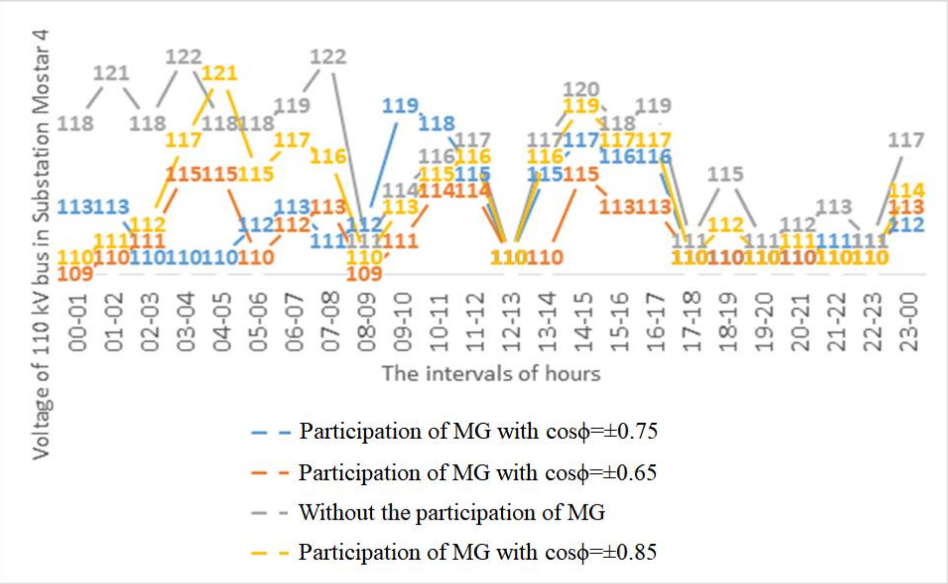


Figure 12. Changes in voltage at the 110 kV bus of the Mostar substation for different participation of MG (plus sign marks the inductive mode and minus sign marks the capacitive mode of operation of RES in MG) in voltage regulation

The maximum calculated voltage was 124 kV for 2 May 2023, 05:00 a.m., without the participation of MG in the regulation of reactive electric power. With the involvement of MG, for the three power factors mentioned, the maximum calculated voltages were 122 kV, 120 kV, and 117 kV.

From the simulation, the benefit of the participation of MG in the regulation of reactive electric power, namely, those parts of EPS to which the MG is connected, is obvious. To realize this benefit, it is necessary to communicate with the system operator and the distribution system operator regarding the reactive electric power (energy) in MG.

All power-generating actors in the normal state adhere to the power factor of 0.95. However, it is urgently necessary to set the rules and criteria by which both MG and RES can be included in the provision of acceptable steady-state voltage limits of the system, in mastering post-contingency voltage deviations, and response during transient voltage states. The transient voltage response criteria must specify, at minimum, a low voltage level and the maximum length of time that transient voltages may remain below that level. The same applies to voltages above nominal ones.

Using the described model based on Bayes' theorem for calculating the available reactive electric power (surplus/deficit) in MG, an analysis of the possible impact of taking the "excess" of reactive electrical energy from EPS in MG for the area of Herzegovina (marked with the number 4 on the map of BH EPS) was made. The injection of reactive electric power of high voltage lines (400 kV, 220 kV, and 100 kV) into the EPS has led to increased voltages in the high voltage part of the EPS, which has very negative consequences on the equipment of the system and its safety.

Using the CASE [58] software package, the operation of BH EPS is simulated in which MG participates with its own inductive and capacitive mode in the voltage regulation of the system.

The voltage changes on the 110 kV bus of the 'Mostar' transformer substation (marked green in Fig. 13) and the voltage changes in the surrounding buses (eight of them) with a nominal voltage of 110 kV are presented in Fig. 13. The allowed operation of the RES-based electric power plants in the capacitive mode in MG allowed the reduction of the voltage 110 kV of the southern part of the BH EPS, which were under elevated voltages in low electrical load conditions. In this way, the newly established distribution of reactive electric power flows and dynamic engagement of RES in MG in terms of reactive electric power has positively affected the voltage profiles of the 110 kV network in EPS (for the 2928th hour, in 2023).

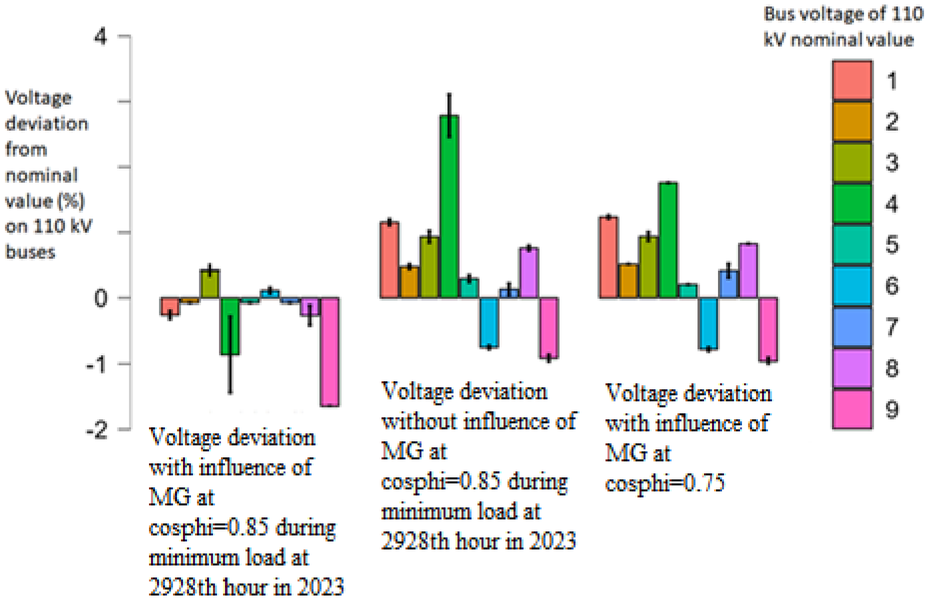


Figure 13. Voltage changes in nine buses of 110 kV BH EPS, Region 4 - Mostar transformer substation and its surrounding - with and without the influence of MG

This example shows the system's resilience to the risks in its operation [59]. The presented approach is possible to minimize failures and limit their impact. Also, the Bayesian approach presented in this paper provides greater flexibility than system operation in which the OR is determined based on the most significant generator outage or other methods based only on statistics or machine learning. Also, the flexibility and controllability of the system have been increased, which adds value to MGs used based on the Bayesian approach presented in this paper.

4. Conclusion

This paper presents a new method to calculate the OR in the form of active and reactive electric power in EPS under the circumstances of participation of RESs in the formed MGs. The proposed algorithm is based on Bayesian probability, a sufficiently helpful mathematical tool to estimate the OR needs. The deterministic approaches to calculate the required OR, which are applied in the EPS of the Balkans, South-East Europe, and most of the world, do not prove to be sufficiently compelling because they either overestimate or underestimate the needs for OR, especially in the environment of intensive RESs penetration into the EPS operation. The presented algorithm provides a quantitative estimate of the required OR and insight into the appropriate spatial distribution of the OR.

The model and analysis presented show that MGs can significantly contribute to solving the problem of frequency and voltage maintenance in EPS at nominal values. In doing so, the requirements for a green transformation of the electric power sector are met while preserving the integrity of the EPS.

However, at the same time, the growing share of RESs in the EPS also reduces the system's inertia, which can significantly affect future stability and reliability. This problem is solved by using virtual inertia; however, for systems in many countries, it is still expensive. Therefore, this proposed method of calculating the required OR in future work will also consider this aspect of reduced system inertia with increasing RES penetration.

The OR calculation approach based on Bayesian probability will gain even more importance in this context. Therefore, the ongoing energy transition and the green energy wave solve environmental problems while threatening the electrical stability and reliability of the system.

Conflict of Interests

No conflict of interest has been expressed by the author.

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