Flexibility and Operating Reserves in Electric Power Systems

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Abstract. Maintaining the efficiency of electric power systems (EPSs) requires some flexibility margin, which decreases in the case of adopting a variety of renewable energy sources (RESs). For this reason, the determination of the EPS flexibility several hours ahead becomes especially urgent. In this study, the flexibility of a 5-node EPS with a four-minute load change during a 6-hour time horizon is calculated. To this end, a probabilistic method based on the analysis of the cumulative probability of the available flexibility is used.

1 Introduction

One of the main characteristics of the flexibility of an electric power system (EPS) is the ability to maintain the efficiency of EPS under changing internal and external factors.

Depending on the purpose of flexibility application, all studies of flexibility can be divided into two groups: long-term planning and real-time. Flexibility metrics can be probabilistic [1] and deterministic [2].

The scientific articles describe different metrics of flexibility, including:

1. Determination of a range of maximum uncertainties within which the system remains flexible for a specified time and a cost threshold [2].
2. Calculation of the insufficient ramping resource expectation (IRRE). Formation of the probability distribution of available flexibility resources for each direction and time horizon [1].
3. Calculation of a flexibility residual, i.e. the difference between the available flexibility and the expected load ramps for each observation and horizon. Then, the determination of the probability that the residual flexibility will be less than zero, which means the probability of insufficient resources in the system [3].
4. Calculation of the ramping rate (ΔR), power (ΔP), and energy (ΔE). These values are used to determine flexibility in EPS [4].
5. Calculation of flexibility sets, which determine the allowed deviations from the current state of the EPS. The method is based on computational geometry using polytopic projections, which requires a limited amount of information exchange between two EPSs, and it can do without central coordination [5].

EPS flexibility is achieved by increasing and properly utilizing power reserves. The calculation of the EPS flexibility requires accurate information about the available power reserves in the EPS and the rules for using these capacities.

This paper presents a quality characteristic of the EPS flexibility, which is calculated by a probabilistic method [1]. The structure of the article is as follows. Section 2 presents an overview of the EPS reserves. Section 3 focuses on advanced energy storage technologies. Section 4 describes the modeling of EPS facilities' flexibility. Section 5 presents the research results. Section 6 gives the conclusion.

2 Reserves of electric power system

Reserves are provided either on-line or in a standby mode. They are used in the case of load increases or generation decreases due to unpredictability or variability of the conditions. In EPS having a large number of variable generation sources (wind, solar), which can unexpectedly increase or decrease power output, it is crucial to have both upward and downward reserves [6].

The operating reserve is the capacity used to maintain active power, which comes in different shapes and sizes. The need for operating reserves arises for many reasons, including the variability and uncertainty of the state variables. The variability is the expected changes in the state variables. The uncertainty is the unexpected changes in the state variables.

Scientific articles provide an overview of the operating reserves used in the USA and Europe [6], [7].

The procedures for the use of operating reserves are set by different entities depending on the operating reserves required, who can provide them, when they should be unfolded and how they are used. The standards are usually based on specific reliability criteria and criteria for acceptable risk but often differ from region to region. Due to the high penetration of renewable energy sources, which have new characteristics for EPS, it is necessary to adjust standard rules and policies to account for the increased variability and uncertainty caused by them. The presented methodologies emphasize how reserve requirements can change with significant penetration of the variable generation in EPS [6].

Ref. [8] presents a methodology for determining the minimum required volumes of active power reserves of the EPS of Russia. According to the given methodology, the system operator determines and places the normative amounts of reserves, which are divided into three kinds according to the degree of maneuverability: spinning reserve, including the reserves of primary, secondary, and tertiary control; hot reserve; and cold reserve.

In an energy system having renewable energy sources, a decrease in the power output from solar and wind farms (due to changes in weather conditions: illumination, strength, and direction of the wind) is determined based on actual (statistical) information within 10 minutes. If a decrease in the power output leads to an emergency imbalance of the active power, then it is considered as a normative disturbance of the second group [9].

3 Advanced energy storage technologies

In [10], the authors describe in detail the EPS flexibility measures and advanced technologies for energy storage. An electricity-to-heat technology enables the excess energy from wind and solar farms to be converted into heat. Power-to-gas technologies produce synthetic methane, which can be used in gas distribution systems. Power -to -hydrogen technology allows hydrogen to be produced and stored for some time. The hydrogen can then be converted back to electricity. Due to vehicle-to-grid technology, energy storage services are provided in a distributed form, which implies the use of electric vehicles.

Siemens Gamesa has launched an ETES (Electric Thermal Energy Storage) pilot facility in Hamburg, Germany. The pilot facility converts electrical energy into hot air using a resistance heater and blower. The hot air heats about 1000 tons of volcanic rock to 750 ° C. The facility can store up to 130 MWh for a week due to effective insulation, according to a company spokesman. During the periods of high electricity demand, the stored thermal energy is to be converted back to electricity by using a steam turbine. This electricity will be sold by a local utility company [11].

The energy company ENERTRAG has launched a thermal energy storage device that allows the utilization of surplus electricity generated by the wind farm and provides heat to the central heating system. The thermal energy storage device is a water tank with a capacity of about one million liters, which is used in the local district heating system. This volume heats up in just a few hours to 93° C. Heating turns on automatically when the wind farm is disconnected from the network. The thermal energy storage device can supply heat to the village for up to two weeks [12].

Sonnen, the largest European manufacturer of home energy storage systems, has commissioned a virtual power plant (VPP) in northeastern Germany. The virtual power plant combines storage batteries into a uniform virtual network, a distributed large-scale storage system. Free volumes of these storage batteries are sold through a digital exchange. For example, according to the weather forecast, the future surplus of wind energy is known. In order not to waste wind energy, the system operator informs about the need for appropriate energy storage. The software logs this request and automatically matches it with the available storage capacity at the Sonnen virtual power plant and calculates how long the surplus wind power will be stored [13].

Scottish startup Gravitricity has announced the start of a pilot gravitational energy storage project at Scotland's largest closed deep-water port. The storage devices work according to the principle used in the pumped-storage power plant, but instead of water, they use solid materials (concrete blocks or environmentally sustainable raw materials, namely waste that would otherwise be sent to landfills). To accumulate energy, the weights are raised, and to release the energy, they are lowered (potential and kinetic energy is converted into electrical energy). The 250 kW prototype will use two 25-tonne weights suspended from a 16-meter tower on steel cables. The industrial Gravitricity system is installed above a shaft 150-1500 m deep [14].

ThyssenKrupp is launching electrolysis plants in the energy market. They will act as a buffer to stabilize the power system: if there is a surplus power output from wind and solar power farms, then hydrogen production will increase. On the contrary, when the electricity demand is high, the plant stops producing hydrogen. Based on the results of the tests, the company claims its water electrolysis technology for the production of green hydrogen meets the criteria for participation in the primary control. A condition is the ability to gain full power for a maximum of 30 seconds and maintain it for at least 15 minutes [15].

The project for energy storage technology developed in [16] involves a 4.5 MW solar power farm, a 4.5 MW/4.5 MWh Li-ion energy storage system, and a 2 MW and 17 MWh hydrogen energy storage system. Excess solar power output will be converted to H_2, which will be stored in a solid material called sodium borohydride ($NaBH_4$). It can absorb hydrogen like a sponge and then release it back. The hydrogen released back is sent to the fuel cell to generate electricity.

The Dutch energy company GreenChoice is going to install ten mobile storage containers with a capacity of 336 kW each next to a small 12 MW Hellegatsplein wind farm. The batteries will be charged directly from wind turbines and will provide ancillary services to the Dutch electricity grid, increasing its flexibility. A specific feature of the project is the mobility of the batteries, the ability to move them to provide various types of services to different clients. The system charging time is 43 minutes [17].

Energy storage systems are essential tools for increasing the flexibility of the power system because they can shave peaks in electricity generation and consumption. Energy storage devices can be classified according to their location. Table 1 shows the classification of energy storage systems.

Table 1 Classification of energy storage systems

Location	Brief characteristic
Near wind and solar farms	Energy storage systems are installed near the wind or solar farms. They are charged directly from wind turbines or solar cells. Thanks to this feature, the generation of electricity is stable around the clock.
Near the consumer	A storage device stores energy over a user-specified period and then returns it when needed. Currently, the technologies are being implemented that allow all home storage devices to be combined into one virtual power plant with a large storage capacity. This technology will enable the system operator to use these batteries. Lithium-ion (Li-Ion) batteries, nickel-cadmium (NiCd) batteries, supercapacitors, electric vehicles are used as storage devices.
Significant nodes of the power system	Energy storage systems that evenly store electricity by converting it into heat, into hydrogen, or use energy to lift loads to a height. These energy storage devices store energy at the moment of its surplus, and give it out at the moment of shortage, by reverse conversion; they are installed near consumers and are capable of supplying heat and electricity to individual settlements.

4 Modeling the flexibility of EPS elements

Model of generator flexibility of a conventional plant

The flexibility of each generator is determined by the power generated over the considered time horizon and is calculated by the formula [1]

$$F_g = V_{i+} * (t - (1-b) * S_i), \quad (1)$$

where V_{i+} is load ramp time (MW/min), t is the considered time horizon, S_i is the startup time (hour), b is the binary on-line variable when a generator is on $b=1$.

Model of battery flexibility

The flexibility of the battery is determined by its state of charge (SOC). If the battery is charged within the specified limits

$$SOC_{min} < SOC(t) < SOC_{max}, \quad (2)$$

then the power output is calculated by the formula:

$$F_B = P_{max} \quad , \quad (3)$$

otherwise:

$$F_B = 0 \quad . \quad (4)$$

Model of system flexibility

The system flexibility is determined as a sum of flexibilities of all facilities in the system

$$F_S = \sum_1^m F_g + \sum_1^n F_B \ , \quad (5)$$

where m is the number of generators at conventional plants, n is the number of batteries.

5 The case studies

In this study, the flexibility of a 5-node EPS (Fig.1) is calculated using the IRRE method. In the proposed network bus 1 is a wind turbine, bus 2 is a generation unit, bus 3 and 4 are loads, bus 5 is the BESS. Bus 2 is a slack bus.

The means of flexibility are the balancing plant and the battery. It is assumed that it takes 4 minutes for the entire available reserve at the balancing plant to be switched on and that it takes 0.01 minutes for the battery to produce maximum power.

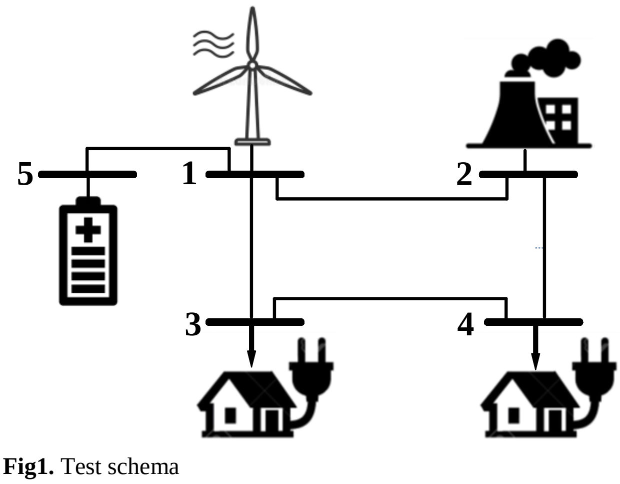

Fig1. Test schema

The work is aimed at determining the EPS flexibility for 6 hours for the case of a four-minute change in the load curves.

Information about flexible resources

The description of the flexible resources requires the following information:

1. Retrospective or simulated data of a flexible resource power output. In this study, simulated data are used.
2. Availability of data for each resource (on, off, how long it will turn on).
3. The upper limit of generation.
4. The lower limit of generation.
5. Startup time of a flexible resource.
6. Power ramp rate (increase).
7. Power ramp rate (decrease).
8. The probability of equipment failure.

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Table 1 shows the characteristics of flexible resources.

Table 1. Characteristics of flexible resources.

№	Characteristic of flexible resources	Means of flexibility	
		generator	**battery**
1	Data on flexible resources	simulated data, 90 snapshots, 4 minutes	
2	Availability of data for each resource	1	1
3	The upper limit of generation (MW)	22	7
4	Startup time	4min	0.01 min
5	Ramp rate	22MW/4 min	7MW/0.01 min
6	The probability of equipment failure	0	0

Creation of a measurement archive

In this study

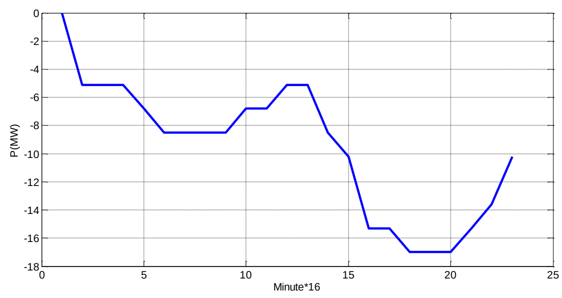
- 60 intervals are considered (5 days a week, 4 weeks a month, 3 months) with a duration of 6 hours.
- 90 snapshots are simulated every 4 minutes (360 minutes).
- Reserves are calculated every 4 minutes.

An algorithm for creating an archive of measurement snapshots is as follows:

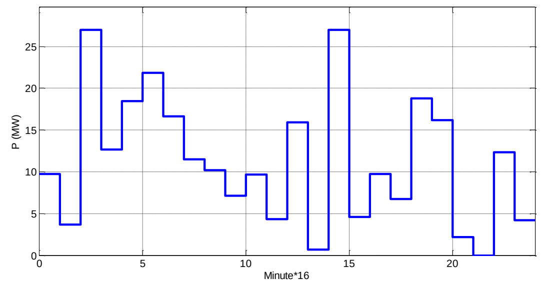
1. Simulate the loads at nodes 3, 4. Figure 2a shows a based load profile at node 3. Simulate power output at the wind farm. Wind turbine characteristics are known, and the wind speed is determined according to the Weibull distribution. Figure 2b shows the power output profile at node 1.
2. Calculate steady state for each point of the given load and generation curves. An obtained set of state variables is taken as true values (y_{true}).
3. Simulate the set of measurements $\bar{y}$ based on the set of y_{true} and information about the location of measurement devices:

$$\bar{y} = y_{true} + a\sigma, \qquad (6)$$

where σ is measurement standard deviation, a is the value obtained by a random number generator, $a \in N(0,1)$. Each set y_{true} is used to simulate four snapshots, which means that four snapshots consist of measurements that differ from each other in the magnitude of the random error.



a) Load profile at node 3



b) Power output profile at node 1

Fig. 2. Load and power output profiles at nodes.

Figure 3 shows a curve of wind speed.

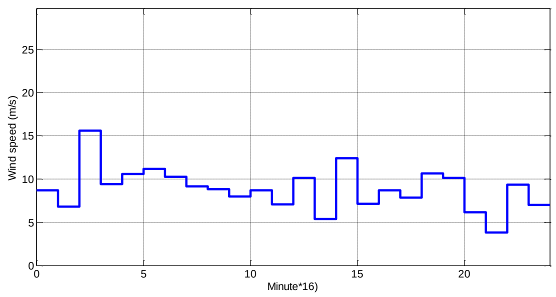


Fig. 3. Wind speed.

Figure 4 shows the SOC value of the battery at node 5 in the base case.

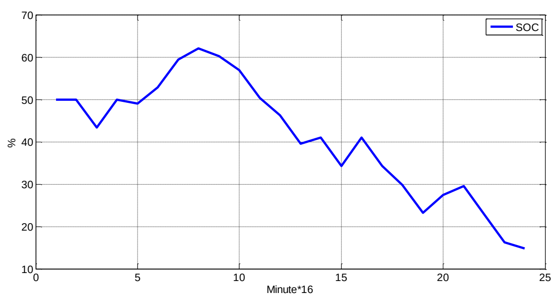


Fig. 4. SOC of the battery at node 5 in the base case.

Figure 5 shows the power output profile and the upper limit of generation at node 2. Figure 6 shows the SOC value of the battery at node 5.

Calculation of the cumulative probability of reserves distribution

The probability of the insufficiency of power system flexibility at each time horizon is the cumulative probability of the system's ability to provide power in the case of changes in the load.

Figure 6 shows a distribution of the available flexible resources for a 6-hour time horizon. This distribution is used to calculate IRRE.

An algorithm for calculating the cumulative probability of the available flexibility is as follows:

1. Calculate reserves at each considered moment (90*60=5400 points). It is assumed that it takes 4 minutes for all available reserves in the power system to be switched on. Power system flexibility is calculated by the formula:

$$F_g = P_2^{max} - P_2 \quad , \tag{7}$$

where $P_2^{max} = 22MW$, P_2 is power output at the balancing plant at a considered moment. Nominal energy that can be stored by the battery is $W_{CAP} = 7MWh$.

2. Classify the obtained values into several groups. Each group integrates the same reserves.
3. Sort the groups in ascending order of the reserve magnitude.
4. Calculate the probability that the given reserve will be available for each group (the larger the group, the higher the probability).
5. Determine the cumulative probability of the available flexibility.

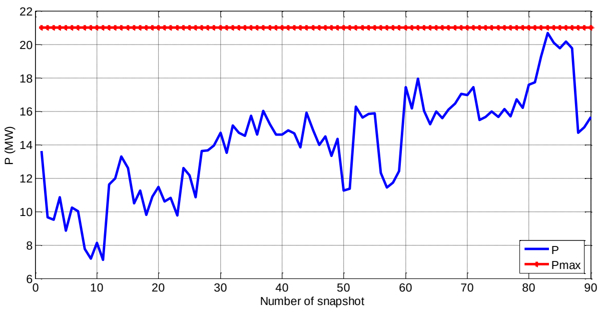


Fig.5. Power output profile and the upper limit of generation at node 2

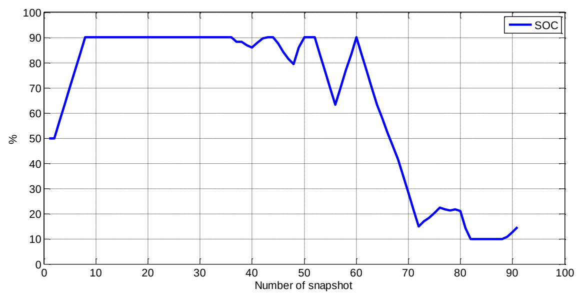


Fig.6. SOC of the battery at node 5

Figure 5 shows that a reserve is available at the balancing plant (node 2) within six hours (90 snapshots). Figure 6 shows that the battery is in a discharging mode at 6 snapshots (82–88) and, therefore, it cannot supply power. Figure 7 shows the distribution, which indicates the probability that x MW or less, of flexible resources, will be available four minutes ahead within the 6-hour time horizon. For example, there is a 26.6% probability that 6 MW or less of flexible resources (56.6% probability that 13 MW or less) will be available any 4 minutes ahead (4 min upward rumps) during a 6-hour time horizon.

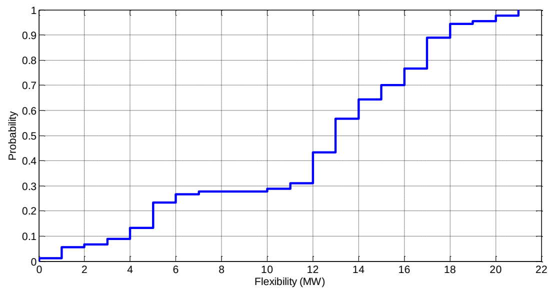


Fig.7. The cumulative probability of the available flexibility

Application of the cumulative function of reserve distribution

Two scenarios were developed for calculating power system flexibility (4-minute upward ramps) using the cumulative probability of the available flexibility (Figure 5).

Scenario 1. Load ramps are 16 MW/4min.

Scenario 2. Load ramps vary from 10 MW/4min to 18 MW/4min.

Scenario 1. Analysis of the graph presented in Figure 5 shows that there is a high probability (70%) that there will not be enough resources to meet the 16 MW load for 6 hours any 4 minutes ahead. It means that in this case, the system will face a shortage of flexibility.

Scenario 2. The probability that there will be insufficient resources to meet the changes in load in a range from 10 MW/4 min to 18 MW/4 min is calculated by the formula:

$$P_{IRRE} = P(18) - P(10), \tag{8}$$

$$P_{IRRE} = 0.95 - 0.29 = 0.63. \tag{9}$$

There is a 63% probability that there will be insufficient reserve to meet the load ramps in the range from 10 MW /4 min to 18 MW /4 min for 6 hours any 4 minutes ahead.

Conclusion

In the context of variability and uncertainty of state variables, operating reserves are required to maintain a power balance in an EPS. When determining the size of operating reserves to calculate the flexibility of EPS, one should take into account the fact that there is no uniform standard for applying the operating reserves in the world.

The article overviews the flexibility measures and advanced energy storage technologies. The analysis of the location of advanced energy storage devices indicates that they are located near wind and solar farms, consumers, and significant EPS nodes.

The cumulative function of the probability distribution of the 5-node EPS flexibility at a 6-hour interval with a four-minute load change was built.

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