1.Paweł PIJARSKI[1], 2.Piotr MILLER[1], 3.Sonata TOLVAIŠIENĖ[2], 4.Piotr KACEJKO[1], 5.Jonas VANAGAS[2]

Lublin University of Technology, Department of Power Engineering (1),
Vilnius Gediminas Technical University, Department of Electrical Engineering (2)
ORCID: 1. 0000-0003-3413-2258; 2. 0000-0001-6208-6290; 3. 0000-0002-8303-0576; 4. 0000-0003-1747-6235; 5. 0000-0001-8913-3595

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A method for quickly determining the individual connection possibilities of power grid nodes

Streszczenie. *W artykule przedstawiono nową, szybką i skuteczną metodykę szacowania dostępnych mocy przyłączeniowych dla źródeł. Są one wyznaczane indywidualnie dla każdego węzła sieci elektroenergetycznej przy założeniu spełnienia niezbędnych ograniczeń. Na przykładzie zmodyfikowanej sieci testowej IEEE-118 zaprezentowano wyniki uzyskane za pomocą proponowanej metodyki. Posiadając takie narzędzie operator sieci będzie mógł sprawnie udzielać odpowiedzi na zapytania inwestorów dotyczące możliwości przyłączenia źródła we wskazanym węźle sieci* ***(Metoda szybkiego wyznaczania indywidualnych możliwości przyłączeniowych węzłów sieci elektroenergetycznej).***

Abstract*. The article presents a new, fast and effective methodology for estimating available connection capacities for sources. They are determined individually for each node of the power grid, assuming that the necessary constraints are met. The results obtained using the proposed methodology are presented on the example of a modified IEEE-118 test network. With such a tool, the network operator will be able to efficiently respond to investors' inquiries regarding the possibility of connecting a source at a given network node.*

Słowa kluczowe: OZE, przeciążenia linii, analiza N-1, bilans mocy.
Keywords: RES, line congestion, N-1 analysis, power balance.

Introduction

The increase in the number of renewable energy sources planned for connection contributes to overloads of power lines and balance problems. Such challenges make it difficult or even impossible to connect further sources. Knowledge about the connection possibilities of individual nodes of the power grid is extremely important and valuable from the point of view of investors. In 2011, an amendment to the Energy Law [1] obliged network operators in Poland to present information on available connection capacities on their websites. These results should be updated quarterly, five years in advance. Various methods of determining them were then developed, described below.

Recently, many potential investors have been looking for a place to implement future investments in renewable sources and energy storage. The authors encounter various situations in their practice. It often happens that a potential investor has in mind several attractive locations for a given source, but lacks knowledge about the technical possibilities of connecting the power grid. Therefore, the question arises: which of the indicated locations will be the most convenient in terms of available connection power? To check this, each of the indicated network nodes should be considered separately, indicating the one with the greatest connection possibilities. This article proposes an original algorithm that allows to solve the problem in question.

This article is organised in such a way that the first section contains an introduction to the analysed problem. The second point is an overview of the methods used so far to determine the available connection capacities. The third section presents the proposed calculation methodology. The fourth part describes the test network. The fifth unit contains the calculation results and their discussion. Finally, a summary and conclusions follow.

Review of literature

The available literature contains various methods of determining the available connection capacities for sources. Generally, they can be divided into two types: simultaneous search for connection possibilities in all nodes of the considered network area and individual determination of maximum connection powers in each node. The individual capabilities of each node can be treated in two ways. One consists in determining the available connection capacities for each node separately, with different combinations of nodes to start the calculations. The other adopts a state in which the designated power in nodes, introduced simultaneously, does not cause any excesses and is the maximum power. The second method involves determining the available connection capacities for each node separately, without introducing the capacities designated in other nodes into the network.

The general partnership Technical Research and Analysis Studio, in Polish: *Pracownia Badań i Analiz Technicznych* (*PBiAT*) *s.j.*, in cooperation with the Department of Planning and Development of the ENEA Operator (Sp. z o. o. or Ltd), created three methods. The first one involves simultaneous input of power to the network nodes of the analysed area. The process ends when one of the branches is overloaded due to the N-1 analysis. The available connection power is the sum of the powers that can be introduced in the nodes of a given area. The advantage of the method is simplicity, but the disadvantage is the large number of possible solutions. The second method is an extension of the first. It consists in introducing the generated power, first in the nodes to which the power flows, and examining the N-1 states until overloads occur. Compared to the previous method, a more even network load and greater accuracy are possible. However, the computational algorithm is more complicated and time-consuming. When selecting the nodes to which power flows, one should expect overloads in their vicinity. The third method takes into account the standard requirements of operators when performing expert opinions. Calculations are performed for each node separately. The assumption is to know the power generated in the remaining nodes. As with the first method, it is simple and understandable. The disadvantages include repeating the calculations after connecting a new source.

An original algorithm, belonging to the group of heuristic algorithms, was also created by PBiAT. It assumes determining the power increment index individually for each node while meeting the required network constraints.

The Institute of Energy, Gdańsk Branch, created the so-called method of coherent nodes ([2], [3]). This method is based on the identification of intercorrelated groups of nodes, in terms of sensitivity coefficients. It involves the gradual connection of a new generation and the analysis of power flow results both after and before connection. The group creation algorithm is based on the identification of the most highly correlated nodes. Then, the generations in individual groups are gradually increased until overloads occur. The disadvantage is that it is time-consuming, but the advantage is the creation of certain areas where sources have a similar impact on the network.

Another method originally planned to be implemented by Energoprojekt Kraków is the so-called incremental method. It is one of the simplest methods for determining available connection capacities. It involves increasing the power in the source connected to a previously selected node until overload occurs. Then, the previously determined value of available power is permanently connected to the analysed node and the remaining nodes in the network are considered similarly. The main disadvantage of the incremental method is that the designated connection capacities vary depending on the order in which individual nodes of the power grid will be tested. To increase the effectiveness of this method, all combinations regarding the order of calculations in the analysed nodes should be considered. The final result should include a maximum solution that determines the connection possibilities of network nodes and meets all assumed constraints. The solution should be determined based on the analysis of the results of all calculation cases. The disadvantage of this method is the relatively long time to obtain the result and the lack of certainty whether the obtained solution is optimal.

Another group of methods are methods that use optimisation [4], [5], [6], [7]. In 2011, a series of three articles [8], [9], [10] was created as a result of work performed for the transmission network operator in Poland. This work developed two approaches. One was based on the linear optimisation method described in [9], and the other was based on the heuristic optimisation method described in [10]. The considered objective function F_{obj} can be written as follows:

$$F_{\text{obj}}(\boldsymbol{x}) = \sum_{j=1}^{N} P_{\mathrm{G}j} \tag{1}$$

where: $P_{\mathrm{G}j}$ – power generated in source j, N – number of sources considered in the optimisation process.

The objective function is the sum of the power in the sources when satisfying the equality constraints $\boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = 0$ and the inequality constraints $\boldsymbol{h}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = 0$, where $\boldsymbol{x}$ is a vector of decision variables, $\boldsymbol{y}$ – a vector of independent variables and $\boldsymbol{z}$ – a vector dependent variables. In each state, the power flow (PF) problem is solved according to the relationship:

$$\boldsymbol{0} = f_{\mathrm{PF}}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) \tag{2}$$

ensuring compliance with the power balance in each network node.

The method based on linear optimisation assumes maximisation of the total power in the considered network nodes while meeting the required network constraints, which include emergency shutdowns of lines and transformers. The C7M test network was analysed. The script was written in the Matlab environment. The Simplex method was used in optimisation calculations. The advantage of this method is short computation time and accuracy of solution for linear problems. The disadvantage, however, is the linearisation of the flow task and the failure to take into account reactive power flows in the calculations. The method based on heuristic optimisation solves the same problem as the linear method described earlier. The simulated annealing algorithm was used in the calculations. The advantage of this method is the high probability of finding the global optimum and the ability to start from a point that does not meet the constraints. A penalty is then added to the objective function. The disadvantage, however, is the relatively long time to obtain a solution.

Based on the literature review, it can be concluded that various methods are used to determine the connection possibilities for sources. Their practical use is determined by the accuracy and time needed to obtain results.

Computational methodology

The original algorithm for determining the value of available connection capacities is based on flow models (current and forecast) in the KDM format used by the Plans program. It was developed in Java Script and runs in the Plans environment using the program's capabilities in calculating power flows and N-1 analysis. The basic assumption adopted by the authors of the algorithm is to maintain the initial balance of active power and the balance of international exchange during the operation of the algorithm. Therefore, the active power imbalance introduced into the network model (the potentially available connection power in the selected network node) is distributed among all CDGU units (Centrally Dispatched Generation Units) occurring in the network model (AGC operation – Automatic Generation Control). A similar operation is also used to load RES units and energy storage (ES) units operating as sources, connected to the currently analysed node and nearby nodes to 100% of their generation capacity, carried out by the algorithm.

The N-1 algorithm, in turn, takes into account operations that eliminate the possibility of creating islands without power supply (ASR-type operations – automatic switching on of the reserve – carried out as a complement to the analysed outages).

The result of the algorithm operation, in addition to the determined value of active power that can be connected in the analysed node, is also an indication of the reason for the power limitation, i.e. information whether the interruption of the algorithm was the result of line overload or an increase in the degree of line overload in the normal state, or was the result of line overload or an increase in the degree of congestion in N-1 states. In each of these cases, the algorithm presents information about the overloaded elements and the inclusions that cause these overloads.

The algorithm can be run with any network model loaded into the Plans program. These may be normal, summer and winter states, current or forecast models. However, it should be noted that the preparation of the model is independent of the operation of the algorithm. Proper preparation of the model, taking into account the increase in network load, all planned network investments, renewable energy sources planned for inclusion, issued conditions and scopes of expertise, all this must be prepared before launching the algorithm. Before running it, you also need to prepare batch files used by the algorithm. These are text files in the Plans program format, with a list of nodes subject to analysis in terms of determining the available connection power, a list of branches disabled during the N-1 analysis, and a file defining the monitored area.

The operation of the algorithm determining the values of available connection powers for a given network area can be presented in the following points (Fig. 2):

1. **Data reading and model preparation stage:**
   a. Selecting and reading data from a file in the NPD (National Power Dispatch) format.
   b. Do you want to load the addition file?
      - Yes – go to the stage of reading the addition file (point **1c**).
      - No – go to point **1d**.

c. Selecting and reading data from the addition file.
d. Should I load the data of the monitored area?
- Yes – go to the stage of reading the data file of the monitored area (point **1e**).
- No – go to step **2**.

e. Selection and reading of monitored area data.

2. Setting the parameters for calculating the power flow (temperature, e.g. 30 degrees, limit overload degree, e.g. 100%, checking only current exceedances, limiting the analysis to the monitored area – if point **1d** has previously been performed) and preliminary calculation of the power flow.
3. Preparation of a table with the initial load level of the lines in the monitored area.
4. Saving the model in a supporting binary file.
5. Selecting and reading from the file the list of nodes for which the analysis of available connection capacities will be carried out. The list of nodes is supplemented with the geographical names of the stations and the list of RES and ES sources that should be increased to 100% of generation during the analysis carried out for a given node.
6. Selecting and reading a file with a list of elements excluded as part of the N-1 analysis. In addition to the actual outages (lines with status -1), the file also defines ASR (Automatic Switching on of the Reserve) operations (lines with status +1) carried out in order to maintain continuity of power supply to consumers who are deprived of power as a result of the analysed outage.
7. Initial N-1 analysis. Its main purpose is to prepare a matrix with recorded values of the line load in the monitored area for individual outages carried out as part of the N-1 analysis.
8. **Main analysis loop – iterations concern subsequent nodes from the list of nodes subject to analysis of available connection capacities**

a. Retrieve the next node from the list of nodes being analysed
b. Is there a list of RES and ES sources associated with the node that should be increased to 100% generation?
- Yes – go to the stage of loading associated sources (point **8c**).
- No – go to point 8d.

c. Procedure for loading combined RES and ES sources to 100% of generation using the AGC procedure, i.e. simultaneous unloading of CDGU sources in order to maintain the generation balance within the model. Sources that are disabled in the model are also loaded and enabled, if they are on the list.
d. Adding a fictitious source to the model in the analysed node. As part of the internal calculation loop, the power of this source will be increased in order to find the available connection power in this node.
e. Internal analysis loop – iterations increase the power of the test source by 1 MW
- Increase the source power by 1 MW.
- Check the number of available CDGU sources and spread (reduce) the generation of these sources within the AGC procedure (maintaining the generation balance within the model).
    - Calculate the power flow in the normal state.
- Check whether any exceedances have occurred. The check uses a saved table with initial line loads. The check uses different criteria depending on the selected scenario. If at least one exceedance occurred – remember the reason for the exceedance and go to point **8f**.
- Perform an N-1 analysis.
- For each exclusion in the N-1 analysis, check whether any exceedances occurred. The check uses a saved matrix with line loads occurring at individual outages. The check uses a saved table with initial line loads. The check uses different criteria depending on the selected **scenario**. If at least one exceedance occurred – remember the reason for the exceedance and go to point **8f**.
- **If there were no exceedances, return to the beginning of the inner loop.**

f. Save information about the available connection capacity in the file (this is the current generation value of the fictitious source reduced by 1 MW) and information about the reason for the limitation (exceedances in the normal state or N-1 analysis).
g. Are there any other nodes on the list of nodes being analysed?
- Yes – reading model data saved in an auxiliary binary file (restoring the initial model state from the binary file) and **returning to the beginning of the main loop** (point 8a).
- No – go to step **9**.

9. THE END.

The criteria used to check the occurrence of exceedances apply to both lines (or transformers) that were already overloaded in the input model and those that were not overloaded. The following scenarios, examined in the article, determine the limit level of acceptable overload or its increase in the case of already overloaded elements, caused by an increase in the power generated in the analysed node. The following criteria were adopted in the article:

1. 10% criterion – the influence of the source should not be greater than 10% for both pre-overloaded and non-overloaded elements,
2. 5% criterion – the influence of the source should not be greater than 5% for both pre-overloaded and non-overloaded elements,
3. 3% criterion – the source influence should not be greater than 3% for both pre-overloaded and non-overloaded elements,
4. 3% and 1% criteria – the influence of the source should not be greater than 3% for non-overloaded elements and 1% for pre-overloaded elements,
5. 1% criterion – the influence of the source should not be greater than 1% for both pre-overloaded and non-overloaded elements,
6. Criterion 1% and 0.5% (new congestion) and 0.5% (existing congestion),
7. 0.5% criterion – the source influence should not be greater than 0.5% for both pre-overloaded and non-overloaded elements,
8. Criterion 1.5 A/1 MVA (transmission network) and 5A (110 kV network) – amperage criterion, examining not the degree of overload, but the specific value of overload in A or MVA,
9. Criterion 1 A/1 MVA (transmission network) and 2 A (110 kV network) – amperage criterion, examining not

the degree of overload, but the specific value of overload in A or MVA.

Most of the above criteria are based on documents specifying the requirements of transmission and distribution network operators for electricity sources connected to the National Power System. These are the so-called DSSCCEO, i.e. **d**ocuments **s**pecifying the **s**cope and **c**onditions for **c**arrying out an **e**xpert **o**pinion on the impact of connecting facilities on the power system. The content of these documents has changed many times over recent years and these changes reflect the criteria adopted in the article. Additionally, the authors introduced criteria no. 1, 2 and 8 to show the possibilities of increasing the potential of available connection capacities in the analyzed power system.

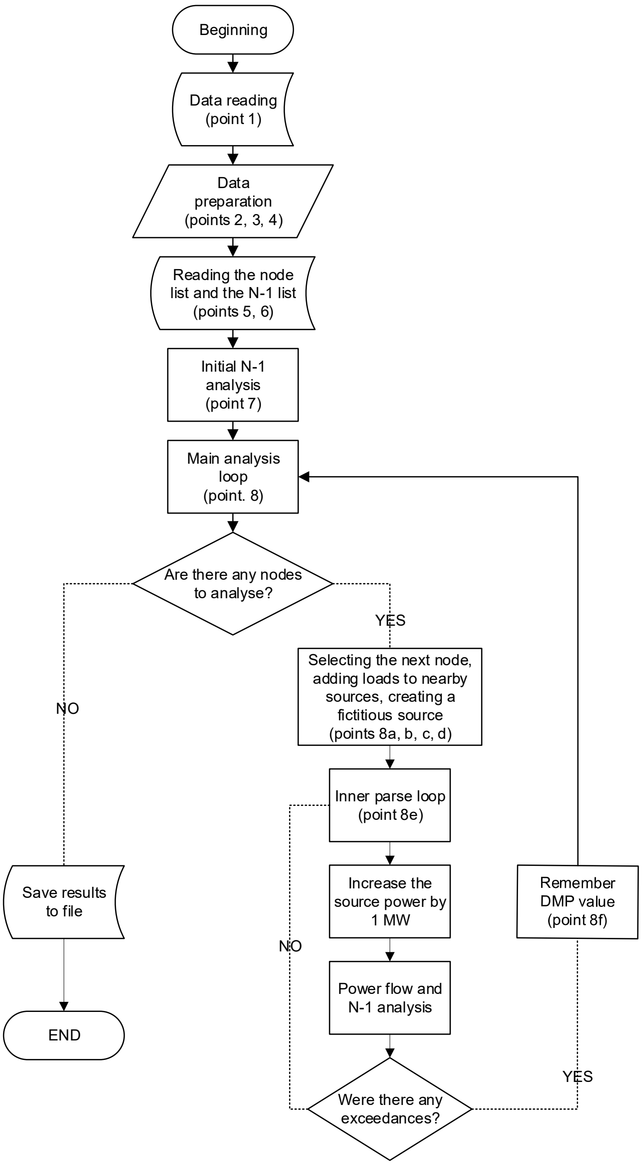

Fig.1. Algorithm for determining available connection capacities, DMP

Test network

The article uses a modified IEEE-18 bus test network [11]. The network diagram is shown in Fig. 2. The parameters of individual network elements were adapted to the parameters of the Polish power grid. The voltage levels were changed to 110 kV, 220 kV and 400 kV. The line sections were modelled using commonly used wire cross-sections, i.e. 120mm^2, 185mm^2 and 240mm^2 (in the case of a 110 kV network), 525mm^2 (for a 220 kV network) and 2x525mm^2 (in the case of a 400 kV line). It was assumed that most lines are designed for an operating temperature of 40°C. Some lines have operating temperatures of 60°C and 80°C, which are marked accordingly in Fig. 2. The load and generation in individual nodes have also been changed.

Calculation results

Calculations were performed for each node of the modified IEEE 118 bus test network and the nine criteria mentioned earlier. The calculation results are presented in Table 1 and Fig. 3. As can be seen in Fig. 3, non-zero values only occur at some network nodes. There is a certain group of nodes in which connection possibilities exist regardless of the criterion used. Based on the results obtained, it can be concluded that the most attractive connection points are nodes no. 44, 52, 82, 95 and 116.

When performing computational analyses, network operators require that they identify those elements that are overloaded or their overload deepens after connecting the analysed source above the permissible values. The maximum differences in the overload of network elements required when performing connection studies in the states after and before connecting the source are small (criterion no. 4, 6 and 9) and their use in practice may lead to the inability to connect a large number of nodes, both in the distribution network as well as transmission. By adopting very rigorous assumptions and taking into account possible calculation errors resulting from the adopted accuracy of the iterative method of the power flow calculation algorithm, it can be said in advance that each considered object will have "some" impact (even marginal) on "one" of the existing lines of the observed network area, and this will be a reason to either refuse to issue connection conditions or to drastically limit generation within a specified period of time. Analyses in the field of flow calculations are characterised by the fact that the considered network operating states, its structure, generation distribution along with the appropriate selection of the composition of generating units, and loads in nodes are selected on the basis of historical data, experience, engineering knowledge, and a previously prepared schedule. It can be said that it is, in a sense, forecasting, which is associated with a particular amount of uncertainty, which in turn affects the accuracy of the analyses performed. Taking the above into account, the measure of the source's impact on the network should be set at a level corresponding to reality, i.e. higher than before, e.g. 5%. In table 1, this corresponds to criterion number 2. The authors believe that even the value of 5% is not overstated and could be taken into account in practice, especially in analyses burdened with a large dose of uncertainty, such as those performed in this article.

The analysed high and highest voltage test network corresponds to the specificity of the Polish power grid in terms of its parameters. On its basis, one of the current problems faced by operators is presented.

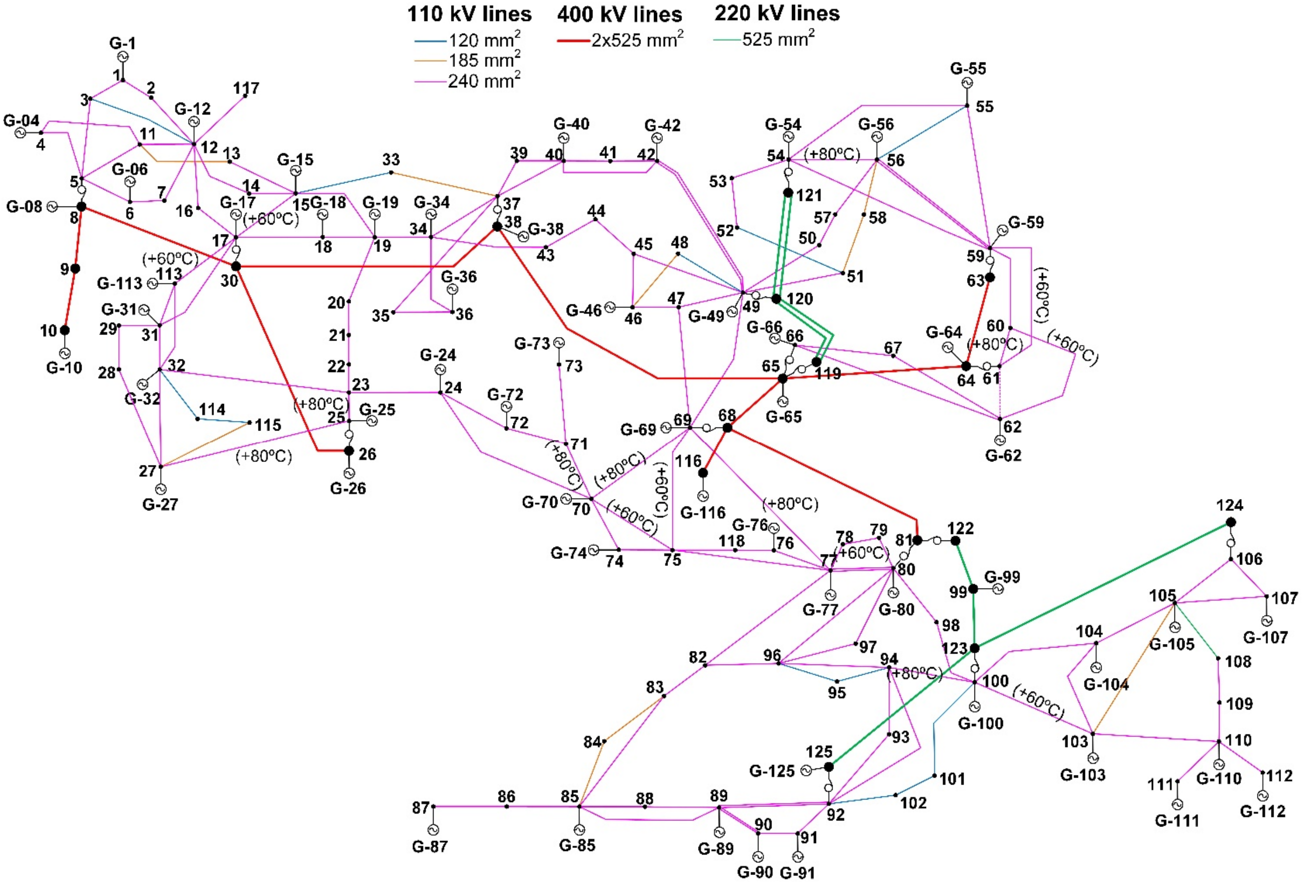

Fig.2. Modified IEEE-118 bus test network [11]

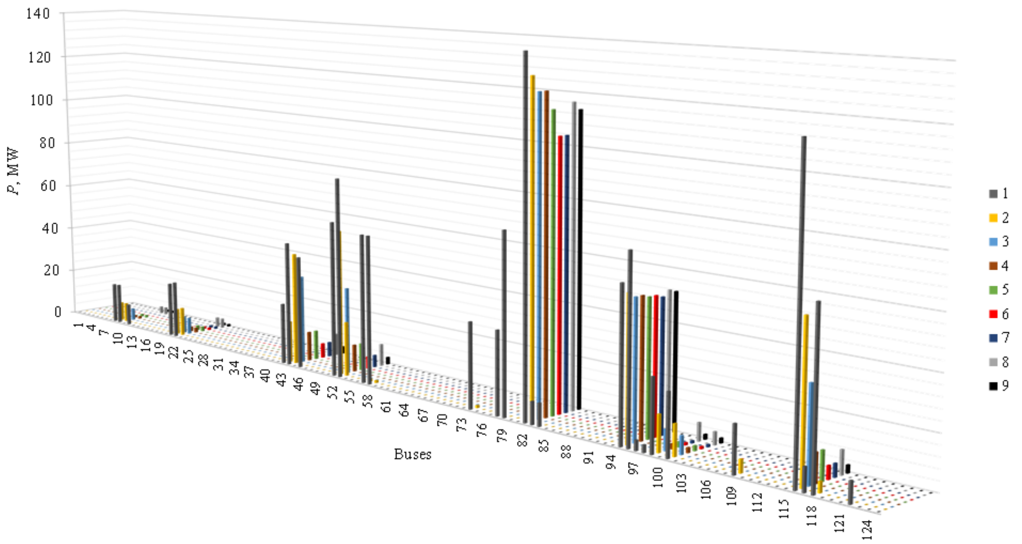

Fig.3. Values of available connection powers in individual nodes of the IEEE 118 bus network

The value of 5% can be justified by the fact that this type of analysis is subject to a significant level of uncertainty, which results primarily from:

- expected network load – in this type of analysis, load values in individual network nodes are assumed based on their changes in the past,
- selection of the composition of generating units – the list of sources operating in the model is adopted on the basis of the operator's current assumptions,
- power distribution in generating units – the level of power generated in each source results from the assumptions made regarding renewable energy generation, so it is difficult to predict what it will be like in the future,
- network operation configuration – it is adopted on the basis of current assumptions, so it is difficult to predict exactly which lines will be turned off and which will be turned on in the future,

- permissible current carrying capacity of power lines – which depends on current weather conditions, i.e. wind speed and direction, sunlight and ambient temperature.

Table 1. Values of available connection powers (in MW) in IEEE 118 bus network nodes

Bus numbers	Variant numbers								
	1	2	3	4	5	6	7	8	9
9	17	8	5	1	1	0	0	3	1
10	17	8	5	1	1	0	0	3	1
12	9	0	0	0	0	0	0	0	0
21	23	11	7	2	2	1	1	4	1
22	24	12	7	2	2	1	1	4	1
43	25	17	0	0	0	0	0	0	0
44	51	46	36	12	12	6	6	9	3
46	46	0	0	0	0	0	0	0	0
52	63	59	35	11	11	5	5	9	3
53	81	22	0	0	0	0	0	0	0
57	60	1	0	0	0	0	0	0	0
58	60	1	0	0	0	0	0	0	0
74	34	1	0	0	0	0	0	0	0
78	33	0	0	0	0	0	0	0	0
79	71	0	0	0	0	0	0	0	0
82	137	128	122	122	115	105	105	117	114
83	9	0	0	0	0	0	0	0	0
84	9	0	0	0	0	0	0	0	0
95	59	55	53	53	52	52	51	53	52
96	71	0	0	0	0	0	0	0	0
97	4	0	0	0	0	0	0	0	0
98	3	0	0	0	0	0	0	0	0
99	28	14	8	2	2	1	1	7	2
101	24	12	7	2	2	1	1	5	2
109	18	5	0	0	0	0	0	0	0
116	116	58	35	11	11	5	5	9	3
117	9	0	0	0	0	0	0	0	0
118	64	4	0	0	0	0	0	0	0
122	8	0	0	0	0	0	0	0	0
Suma	1173	462	320	219	211	177	176	223	183

For comparison, calculations were also made assuming the permissible impact of the source on the network equal to 10% (criterion number 1). This value was once considered acceptable by the operator for computational analyses characterised by uncertainty. With this value, the available connection capacities also appear in other network nodes. As mentioned earlier, in many network nodes the connection capacities are equal to 0MW. This may be incomprehensible, especially in the case of nodes where there are no other sources nearby. As an example, node no. 83 was considered, where for eight criteria (criteria 2 to 9) the connection power is 0MW, while for the first criterion it is 9MW. The reason for this is the disconnection of the 220 kV line 99-122 and the overload of the 110 kV line 94-95. This means that the available connection power depends in some cases on the overload of lines distant from the tested node. The reason for power limitation does not have to be overload of the nearest lines. If an overloaded line is sensitive to small changes in generation at distant nodes, then a strict requirement as to the influence of the source on the network branches contributes to the lack of connection possibilities.

The following factors influence the overload of lines distant from the tested node:

- location of the balancing node and the function performed by this node,
- power values generated in existing sources,
- allowable capacity of network branches,
- place of connection of the analyzed source,
- network configuration,
- change in voltage values in individual network nodes,
- change in power losses,
- change in load at individual network nodes.

Of all the above-mentioned factors, the balancing node (node number 10) can be eliminated by spreading the resulting imbalance to other power plants. In these calculations, it was assumed that these functions will be performed by classic sources, connected at nodes no. 8, 26, 65, 99, 100, 116. By using other power plants to cover the power imbalance in the network, the obtained results become more realistic. In fact, it is the power plants operating with a power lower than the maximum that participate in the power balancing process. The problem of overloading lines distant from the tested node often occurs when performing technical analyses. It also results from the fact that network operators require that nearby sources, constituting the so-called generation background, they usually worked at a higher power than distant sources. This contributes to "pushing" excess power generated from the test area towards other areas. This, in turn, causes such changes in power flows in further areas that lines located further away may become overloaded. Often, the impact of the considered source on such overloads is small (a few percent), but important from the operators' point of view. Another important aspect that should be solved in practice is knowledge about neighboring areas. As previously mentioned, available connection capacities are determined by each operator separately. This means that the results obtained are treated as estimates. For the obtained results to be accurate and reliable, calculations should be performed uniformly and simultaneously in the entire power system. This is made possible by the proposed methodology. Any planned changes in the network would then be taken into account in an accurate manner reflecting its expected condition as a whole and not only in a certain area constituting the assets of a given operator. Therefore, determining the Available Transfer Capacity (ATC) becomes an important issue [12]. Knowledge about transmission capacities between individual areas significantly affects the permissible connection capacities. It may turn out that the connection possibilities of a given area depend on the exchange lines between the areas, and not on the permissible capacities of the lines located inside the considered area. The presented calculation results take into account the previously described factors. Assuming the proposed value of the impact of the analyzed source on the network at the level of 5%, it can be said that the allowable connection capacity for the entire network is 462 MW (criterion 2 in table 1). If the current requirements corresponding to criterion 9 in table 1 are taken into account, the connection possibilities are reduced to 183 MW. The difference in the results obtained, with a small risk of error, is significant because it amounts to 279MW.

Summary

Since 2011, operators in Poland have been obliged to publish available connection capacities for sources. These values should be updated quarterly in advance of every five years. Based on the results posted on websites, it can be concluded that most of them are zero values. At the same time, the operators inform that these are estimated values and the basis for issuing connection conditions should be an expert opinion. Therefore, investors are not discouraged by the published results and try to obtain more reliable values by ordering additional analyses. The proprietary algorithm for determining the available connection options proposed in this article allows you to answer the question of identifying the most attractive node of the analyzed network area. It enables the investor to make the right business decision regarding the location of a potential investment. The proposed methodology is flexible. Using it, you can freely shape the size of the analyzed network area, both in terms of environmental monitoring and N-1 analysis. The generation background (surrounding sources) can also be appropriately loaded depending on the distance from the node under consideration. Comparing it with other algorithms, it can be said that it is distinguished by its originality, practical usefulness, and relatively short time to obtain results. It can bring benefits not only to potential investors but also to network operators. It enables determining the maximum connection possibilities in a single network node while flexible shaping of technical requirements.

***Authors**: dr hab. eng. Paweł Pijarski, Lublin University of Technology, Department of Power Engineering, Nadbystrzycka 38a, 20-618 Lublin, E-mail: p.pijarski@pollub.pl; dr hab. eng. Piotr Miller, Lublin University of Technology, Department of Power Engineering, Nadbystrzycka 38a, 20-618 Lublin, E-mail: p.miller@pollub.pl; Prof. dr Sonata Tolvaišienė, Vilnius Gediminas Technical University, Department of Electrical Engineering, Saulėtekio al. 11, LT-10223 Vilnius, E-mail: sonata.tolvaisiene@vilniustech.lt; prof. dr hab. eng. Piotr Kacejko, Lublin University of Technology, Department of Power Engineering, Nadbystrzycka 38a, 20-618 Lublin, E-mail: p.kacejko@pollub.pl; doc. dr Jonas Vanagas, Vilnius Gediminas Technical University, Department of Electrical Engineering, Saulėtekio al. 11, LT-10223 Vilnius, E-mail: jonas.vanagas@vilniustech.lt.*

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