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The impact of renewable energy sources on the overload of high voltage lines – power flow tracking versus direct current method

PAWEŁ PIJARSKI [1]✉, CANDRA SAIGUSTIA [1], PIOTR KACEJKO [1], LUBOMIR BENA [2], ADRIAN BELOWSKI [1]

[1] *Department of Power Engineering, Lublin University of Technology Nadbystrzycka 38A str., 20-618 Lublin, Poland*

[2] *Department of Electric Power Engineering, Technical University of Kosice Letna 9 str., 042 00 Kosice, Slovakia*

e-mail: {✉ p.pijarski/d607/p.kacejko/a.belowski}@pollub.pl, lubomir.bena@tuke.sk

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Abstract: Studying the impact of renewable energy sources planned to be connected to the grid, requires the preparation of expert opinions. The task of this opinion is to verify that there are possibilities enabling the connection of the considered source to the network. Each opinion is required to take into account other facilities and those sources which were previously connected to the grid or connection agreement were signed with them. The need to take into account such a large number of sources contributes to potential thermal overloads of high-voltage lines. Sometimes these overloads are insignificant, but in certain situations it turns out that their occurrence may be a reason for refusing to sign connection agreements for new sources. According to network operators, their presence may constitute a threat to the operational security of the grid. The article presents the use of the method of tracking active power flows and the DC method of determining power flows to estimate the impact of these sources on thermal overloading of lines. Using of the IEEE-118 test network, selected nodes were analysed where connecting sources might significantly worsen overloads previously observed or would cause new overloads. The proposed approach will enable potential investors to make proper decisions regarding selection of source connection points. Combining the results obtained by both methods at the same time will allow for the indication of appropriate connection nodes for sources from the point of view of minimising the number of overloaded lines and prospective costs of their uprating.

Key words: current overloads, direct current method, power flows, power lines, sensitivity analyses, tracking power flows

1. Introduction

The continuous development of renewable energy sources and energy storage contributes to an increase in the share green energy in the overall energy balance and thus a reduction of greenhouse gas emissions. The increasing number of RESs in the system, scattered throughout the area, increases their diversity and diversification, enhances the installed capacity and reduces power losses in the network. It also has some negative effects, such as potential overload of branches (mainly lines but also power transformers). The occurrence of overloads of the permissible capacity of branches is often the result of the removal of significant power from these sources and the low operating temperature of power lines, which translates into their relatively low thermal capacity. If this is combined with unfavourable weather conditions (such as high ambient temperature, high sunlight, low wind speed, wind direction parallel to the cable axis) and an emergency (e.g. contingency analysis), thermal overload is possible. In their engineering practice, the authors of this article analyse the impact of new sources on power system operation. The assumptions for the expert opinions assume that they take into account all sources located in the immediate vicinity of the considered facility and sources located further away, constituting the so-called generational background. The power distribution in the sources depends on the type of calculation model (summer period, winter period, ambient temperature value, load peak, load valley), the operation schedule of classical units and the type of generation technology. The calculations assume different years of analysis. They are usually forecast models that go several years into the future. This, of course, requires taking into account the investment plans of network operators, which assume the upgrading of existing elements of the power system or the construction of new ones. It is often the case that the dynamics of network investments is lower than the dynamics related to the development and connection of renewable energy sources and energy storage facilities. As a result, there are potential technical problems (including mainly line overloads) and balance problems, resulting in difficulties in meeting the power balance in the entire power system. When talking about failure to meet the power balance, we mean the excess of power generated over the received power, along with power losses. Taking the above into account, the results of many expert opinions indicate the real possibility of thermal overloads on power lines, which may occur after connecting the planned RESs.

There is, in fact, an EU regulation [1] allowing the power redispatching in sources in the event of a threat to the operation of the power system, but this entails the need to pay the owners of the sources financial recompense in this respect. The financial recompense is intended to compensate for losses resulting from curtailed electricity production. The funds are then paid by the Operator who ordered the generation curtailment. In some countries, the UE regulations [1], are not used in each case. They are handled in such a way that the owners of the facilities must agree to possible curtailment of generation during the operation of the source. Such provisions are often included in the connection agreement. In practice, however, operators do not have appropriate algorithms to select the sources that are responsible for the line thermal overloaded. Sometimes the resulting overloads result directly from the connection of the considered facility, but sometimes it is not so obvious due to the fact that the considered source is located at a significant distance from the overloaded lines. It is then difficult to say clearly and with high probability what the reason for such overload is. In the article, the authors try to determine the reasons for thermal overloads and explain the contribution of the analysed source to them. The problem related to planning the connection of new renewable energy sources and energy storage facilities in Poland has been particularly visible in the last few years. The number of connection refusals is significant and results not only from significant line overloads but also from small current overloads of elements located further away. It should be said that each time a source is connected to the power grid or its structure is modified, the power flows will change. This change is most felt and noticeable in its vicinity. Changes in power flow in elements located further away are also observed. It can be said that power flows from the considered source into the network, and thus the line overloads, depend not only on the direct impact of the considered element, but also on other factors described later in the article.

The article is organised in such a way that the first point describes the problem, the advisability of its solution. The second section contains a literature review related to the topic under consideration. The third section describes the calculation methods. The fourth section presents the calculation results. The fifth point summarises the considerations.

2. Literature review

The original method for determining the impact of work planned to connect a RES source proposed in this article was developed as part of various practical analyses performed by the authors. This topic is closely related to sensitivity testing in power engineering, which involves determining changes in a given quantity, e.g. electrical, as a result of a change in another quantity. In the case of this work, the sensitivity of the impact of changes in power generated in the source(s) on overloads (loads) of power lines and transformers is examined.

In the available literature, one can find articles related in some sense to the topic under consideration, for example:

– sensitivity analyses in the power industry [2–6],
– redispatching the power of sources [7–11],
– optimisation of power distribution in generating sources [7, 12–14],
– optimal change of network topology (reconfiguration) [15–18],
– application of the power flow tracking method [7, 19],
– application of methods based on artificial intelligence [14, 20, 21],
– use of impedance coefficients [15, 19],
– use of phase shifters to control active power flows [13, 21, 22],
– intuitive or "manual" determination of sensitivity of power flows in lines [19, 23].

Generally, the works found in the literature mainly concern either the optimisation or tracking of power flows or the search for appropriate coefficients, and less frequently, reconfiguration. In recent years, methods based on artificial intelligence, such as machine learning methods, have been increasingly used.

The issues considered in this article belong to the class of sensitive problems. Sensitivity generally means the magnitude of the impact of one quantity on another. This quantitative impact can be measured by various coefficients, the value of which can be given in dimensionless units, e.g. in the range from 0 to 1 (the higher the value, the greater the sensitivity). Sensitivity analyses in the power system have been studied for a long time, as evidenced by, for example, work [4]. It considered the theory of sensitivity from the point of view of the impact of one variable on another and the sensitivity of operating costs depending on variable demand and generation in the system.

Sensitivity analyses were also performed, for example, in [2], where optimal planning of a network containing renewable energy sources was made, taking into account the DLR (dynamic line rating). Similar research in relation to the optimisation of the operation of the power system in the context of various scenarios was proceeded in article [5]. The sensitivity study involved determining the impact of weather conditions on the management of network operation. In study [3] the authors reviewed the literature on methods for sensitivity analyses in the power system, indicated the most common of them and presented an appropriate example. The sensitivity of the total production cost to changes in reactive power in optimally located capacitors was investigated in [6]. Another group of works concerns the optimisation of the operation of the power grid by optimising power distribution in generating sources and redispatching. In the era of connecting an increasing number of renewable energy sources to the grid, situations (especially emergencies) sometimes occur in which power lines or transformers are overloaded. It is then necessary to redispatch and search for the optimal power distribution in the sources. This type of analyses was performed, among others, in works [7, 9, 19, 24–27]. The methodology of changing the network configuration in order to relieve overloaded power lines was used, among others, in the works [15, 28–31]. Another group of methods are methods based on tracking power flows [7, 19]. On their basis, the contribution coefficients of individual sources in the line load can be determined. Methods based on artificial intelligence are also used to eliminate thermal overloads. In the works [20, 32–34] fuzzy logic and expert systems were used for this purpose. The impedance coefficient method was used in the works [15, 19]. The possibility of adjusting the active power in phase shifters was also used to eliminate line overloads, among others in the works [21, 22]. "Manual" intuitive methods based on engineering experience are also used [19, 23].

In general, it can be said that in the literature it is difficult to find a comprehensive methodology that allows estimating the impact of renewable energy sources on the overloaded of overhead power lines, also from the point of view of the occurrence of emergency states, i.e. different configurations of network operation. At the stage of planning of RES installations, investors are forced to present financial institutions with analyses specifying potential capacity limitations in order to obtain loans enabling the implementation of the planned investment. Banks expect potential clients to provide expert analyses proving the profitability of the investment. This article meets these expectations and indicates the direction and appropriate approach to identify attractive connection locations for RESs from the point of view of minimising power limitations in emergency and abnormal situations.

3. Calculation methods

As mentioned earlier, various methods can be used to solve the problem considered in this article. This work uses methods for tracking power flows and a method based on assumptions typical of the DC method of determining power flows. They are presented later.

3.1. Power flow tracking method

In the early 1990s, the method of tracking power flows began to be introduced into the power industry [35–37]. The English term "tracing" is also used in the description of the method. The authors of the method gave a hypothetical example of colouring the water in different colours in streams flowing into the main riverbed, and then filtering the water downstream and analysing its colour in order to determine the share of individual streams in the total flow. It can be stated that the division of power flow into coloured streams in the case of simple network systems is natural and understandable. In the case of a radial network, distinguishing the power generated in individual sources is not a major problem. In closed systems, intuitive operation is difficult. For networks with a more complex structure, it is necessary to use an appropriate algorithm, the essence of which is to determine the vector of "gross" nodal flows P (e.g. upstream type), its distribution matrix $\boldsymbol{A}_{\mathrm{u}}$ linking abstract (though understandable) nodal flows with specific power sources, according to the equation linear [7, 19, 35, 36]:

$$\boldsymbol{A}_{\mathrm{u}} \cdot \boldsymbol{P} = \boldsymbol{P}_{\mathrm{G}}. \tag{1}$$

The inversion operation replaces the tedious task of tracking by feel, directly relating nodal flows to the power generated at individual sources.

$$\boldsymbol{P} = \boldsymbol{A}_{\mathrm{u}}^{-1}\boldsymbol{P}_{\mathrm{G}}. \tag{2}$$

Having the nodal powers, in the next step the gross power flowing through the considered branch i–l is determined from the following relationship:

$$P_{il} \approx \frac{P_{il}}{P_i^{\Rightarrow}} \cdot \sum_{k \in N} a_{\mathrm{u}ik} \cdot P_{\mathrm{G}k} = \sum_{k \in N} \left(u_{il,k} \cdot P_{\mathrm{G}k} \right), \tag{3}$$

where $u_{il,k}$ is the coefficient determining the use of branch i–l by the source located in node k (share coefficient), which is expressed as:

$$u_{il,k} = \frac{P_{il}}{P_i^{\Rightarrow}} \cdot a_{\mathrm{u}ik}, \tag{4}$$

P_{il} is the active power flowing through the considered branch i–l, $P_{\mathrm{G}k}$ is the active power generated by the source connected at node k, $a_{\mathrm{u}ik}$ represents the terms of the $\boldsymbol{A}_{\mathrm{u}}$ distribution matrix, which are determined from the relationship.

$$a_{\mathrm{u}ij} = \begin{cases} 1, & i = j \\ -\dfrac{\left|P_{ji}\right|}{P_j^{\Rightarrow}}, & P_j^{\Rightarrow} \neq 0 \\ 0, & \text{in other cases} \end{cases}, \tag{5}$$

where: P_{ji} is the active power in branch i–j (taken from node j), $P_j^{\Rightarrow}$ is the active power flowing through node j.

It should be noted that in a tracing method application, the analysed line does not have to have a direct connection to the node to which the source is connected. The described situation is presented in Fig. 1 (the selected source in node k and the line connecting nodes i–l are marked in red). For distinction, another source (marked in green) connected at node r is also shown along with its $a_{\mathrm{u}ir}$ term of the $\boldsymbol{A}_{\mathrm{u}}$ distribution matrix.

The total power flow in the i–l branch is the sum of the products of the power generated in the generating sources and their share factors. If the power tracking operation is applied to all sources

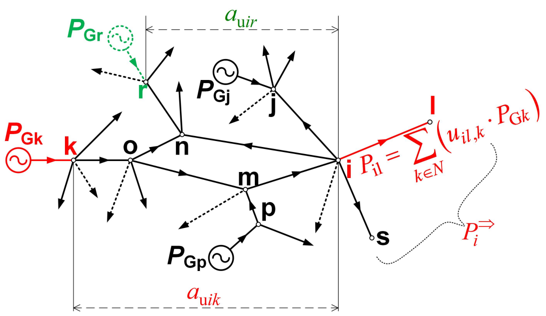


Fig. 1. General illustration of the power flow tracking method

in the network, then each of them can be assigned a contribution factor u, which provides the most important information about whether the considered source significantly influences the resulting overloading of power lines. Generally speaking, this method allows one to select sources that actually influence the overload of power lines. Later in the article, the results obtained with this method will be compared with the method based on assumptions typical of the constant current method of determining power flows, which is described in the next section.

3.2. Method based on assumptions typical for the DC method of determining power flows

This method uses the basic nodal equation for determining power flows:

$$\underline{S}_i = P_i + jQ_i = \sum_{j=1}^{n} U_i \cdot U_j \cdot Y_{ij} \cdot e^{j(\delta_i - \delta_j - \mu_{ij})}, \tag{6}$$

where: S_i denotes the apparent nodal power, P_i denotes the active nodal power, Q_i denotes the nodal reactive power, U_i, U_j denote the voltage moduli at nodes i and j, respectively, δ_i, δ_j, denote the arguments of the voltage vectors at nodes i and j, respectively, Y_{ij} denotes the branch admittance modulus i–j, μ_{ij} denotes the admittance argument of branch i–j.

The problem considered in this work concerns active power flows. They use Eq. (6), the dependence on active power P_i will take the form:

$$P_i = \sum_{j=1}^{n} U_i \cdot U_j \cdot Y_{ij} \cdot \cos(\delta_i - \delta_j - \mu_{ij}). \tag{7}$$

The direct current method (also called the DC method) allows for linearisation of the flow task by applying appropriate simplifying assumptions, such as [38–42]:

– voltage modules in all network nodes are the same and equal to the rated voltage ($U_i = U_{ni}$),
– the differences in the nodal voltage arguments are small, hence the assumption that:

$$\sin\left(\delta_i - \delta_j\right) \approx \left(\delta_i - \delta_j\right), \quad \cos\left(\delta_i - \delta_j\right) \approx 1, \tag{8}$$

– the resistances of lines and transformers are many times smaller than the reactance, therefore it is assumed that the resistance of the elements is equal to zero, the transverse elements are also omitted, therefore the own and mutual conductance elements of the nodal admittance matrix have zero values. Therefore, the branch admittances are the inverse of the reactance, i.e. $Y_{ij} = 1/X_{ij}$, and $\mu_{ij} = -90°$.

Taking into account the simplifying assumptions presented above, Eq. (7) will take the form:

$$P_i \approx U_\mathrm{n}^2 \cdot \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{1}{X_{ij}} \cdot \left(\delta_i - \delta_j\right). \tag{9}$$

As a result of the adopted simplifications, active power P_{ij} and current flows I_{ij} (in branch i–j) are determined according to the following relationships:

$$P_{ij} = U_\mathrm{n}^2 \cdot \frac{1}{X_{ij}} \cdot \left(\delta_i - \delta_j\right), \tag{10}$$

$$I_{ij} = U_\mathrm{n} \cdot \frac{1}{X_{ij}} \cdot \left(\delta_i - \delta_j\right). \tag{11}$$

The unknowns are the angles of voltage vectors δ_i, δ_j in individual network nodes. They can be determined after appropriate transformations, described later.

The general matrix notation of the equation for active nodal power $\boldsymbol{P}$ is as follows:

$$\boldsymbol{P} = U_\mathrm{n}^2 \cdot \boldsymbol{Y} \cdot \boldsymbol{\delta}, \tag{12}$$

where $\boldsymbol{Y}$ is the admittance matrix of the network model.

After transformation, the matrix relationship on δ will take the form:

$$\boldsymbol{\delta} = \frac{1}{U_\mathrm{n}^2} \cdot \boldsymbol{Y}^{-1} \cdot \boldsymbol{P} = \frac{1}{U_\mathrm{n}^2} \cdot \boldsymbol{Z} \cdot \boldsymbol{P}, \tag{13}$$

where $\boldsymbol{Z}$ is the impedance matrix of the network model.

The arguments δ_i, δ_j can therefore be expressed in the following relationships:

$$\begin{aligned} \delta_i &= \frac{1}{U_\mathrm{n}^2} \cdot \left(Z_{i1} \cdot P_1 + Z_{i2} \cdot P_2 + \ldots + Z_{i(n_\mathrm{G}-1+n_\mathrm{L})} \cdot P_{(n_\mathrm{G}-1+n_\mathrm{L})}\right), \\ \delta_j &= \frac{1}{U_\mathrm{n}^2} \cdot \left(Z_{j1} \cdot P_1 + Z_{j2} \cdot P_2 + \ldots + Z_{j(n_\mathrm{G}-1+n_\mathrm{L})} \cdot P_{(n_\mathrm{G}-1+n_\mathrm{L})}\right), \end{aligned} \tag{14}$$

where: Z_{kl} stands for the appropriate term of the impedance matrix, P_l stands for the active power generated or consumed, the n_G index refers to the sources, the n_L index refers to the loads.

The elements of the power vector corresponding to the generating nodes should be included with the "+" sign, while the power vector elements corresponding to the receiving nodes should be included with the "-" sign.

Therefore, the current flowing in branch i–j, after taking into account the dependence on the phase angles δ_i and δ_j, is expressed by the following formula:

$$I_{ij} = \frac{1}{X_{ij}} \cdot \frac{1}{\sqrt{3} \cdot U_\mathrm{n}} \cdot \left[\left(Z_{1i} - Z_{1j}\right) \cdot P_1 + \ldots + \left(Z_{(n_\mathrm{G}-1+N_\mathrm{L})i} - Z_{(n_\mathrm{G}-1+N_\mathrm{L})j}\right) \cdot P_{(n_\mathrm{G}-1+n_\mathrm{L})}\right]. \tag{15}$$

Similarly, to the method of tracking power flows described in point (3.1), the coefficient $c_{(ij)k}$ can be introduced, determining the share of a given source connected to node k in the loading of line i–j:

$$c_{(ij)k} = \frac{1}{\sqrt{3} \cdot U_{\mathrm{n}}} \cdot \frac{\left(Z_{ki} - Z_{kj}\right)}{X_{ij}}. \tag{16}$$

The dependence for the current flowing in line i–j will then take the form:

$$I_{ij} = c_{(ij)1} \cdot P_1 + c_{(ij)2} \cdot P_2 + \ldots + c_{(ij)(n_{\mathrm{G}}-1+n_{\mathrm{L}})} \cdot P_{(n_{\mathrm{G}}-1+n_{\mathrm{L}})}. \tag{17}$$

Therefore, by changing the power generated in the source connected to node k by the value $\Delta P_{k\mathrm{G}}$, there will be a change in the current value ΔI_{ij} in line i–j by a value that can be determined from the following relationship:

$$\Delta I_{ij} = c_{(ij)k} \cdot \Delta P_{k\mathrm{G}}. \tag{18}$$

Based on relationship (17), it can be concluded that in the DC method the relationship between the change in the current flowing in the branch and the change in power in the considered source is linear. Therefore, the impact of individual sources on power line overloads can easily be determined. However, it should be noted that the DC method is less accurate but simple and fast. In some practical situations, it may not be about accuracy but about solving the problem quickly and effectively. The use of a method that is subject to some error but is much faster is a compromise that allows one to efficiently achieve the intended goal.

4. Results and discussion

4.1. General information

A modified IEEE-118 bus test network [43] was used for calculations, shown in Fig. 2, Fig. 4, Fig. 6. The original IEEE-118 bus network was subjected to changes aimed at adapting its parameters to the parameters of the networks operating in Poland. The voltage levels were changed to 400 kV, 220 kV and 110 kV, and the cross-sections and load capacities of the line wires were changed. The total network load was also proportionally adjusted to the load that occurs in the Polish power system. Different levels of network voltage and different cross-sections of power line wires are marked in different colours in Fig. 2, Fig. 4, Fig. 6.

As part of the calculations, three different points of connection of RESs (different rated power) were considered in selected emergency states, which may determine the refusal to issue conditions for connecting the source to the power grid. The authors' assumption when choosing the three cases indicated was to consider states in which both the number of overloaded lines and the congestion values are small (case 1 and 2) and states in which the number of overloaded lines and the congestion values are significant (case 3).

4.2. Case 1

In the first step, a 30 MW source was connected at 110 kV node number 55 (Fig. 2). During the N-1 analysis in the system without the considered source, the shutdown of the 400 kV line 38–65 resulted in an overload of the 110 kV line 113–17 by 17%. This overload depends mainly on the

G-113 source, as shown by both the power flow tracking method and the DC method. Connecting the planned RES source with a relatively low power of 30 MW at node no. 55 causes the overload of the 110 kV line 113–17 to increase to 20.5% and the overload of another 110 kV line 23–24 (by 6%) marked with a bold purple line in Fig. 2. The sources responsible for the overload of the indicated lines, identified using the power flow tracking method, are included in Table 1.

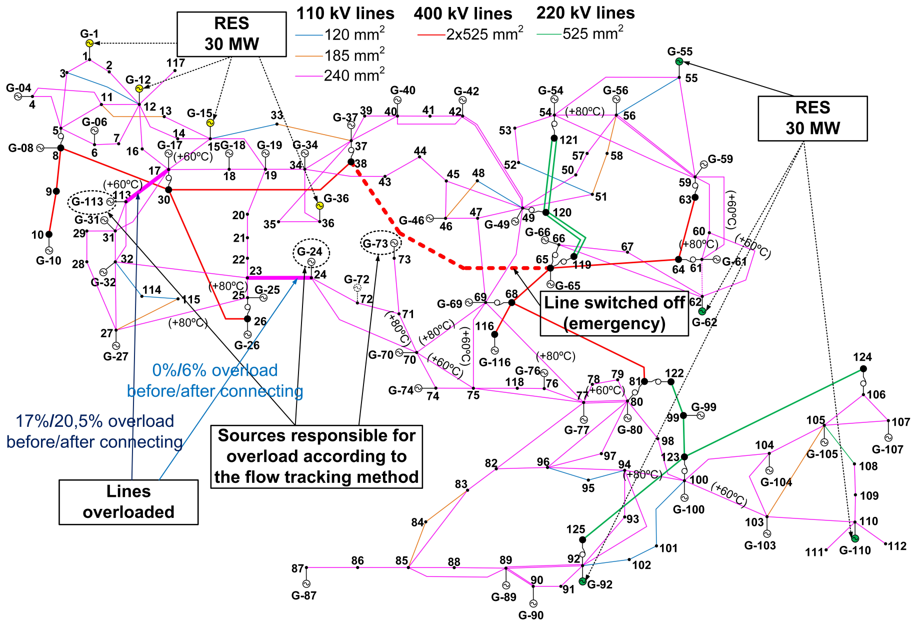


Fig. 2. Diagram of the IEEE 118-bus network with a marked 30 MW source connected at node 55 and disconnected by the 400 kV line 38–65

Table 1. List of overloaded lines with the contribution of the individual sources responsible for the overloads, according to the power flow tracking method (the participation coefficients were calculated according to Eq. (4)

Line overloaded	**Source**								
	G-55	G-24	G-32	G-65	G-69	G-70	G-73	G-113	G-116
From 113 to 17	**0**	0.02	0.04	0	0	0.01	0.014	0.989	0
From 24 to 23	**0**	1	0	0.004	0.048	0.297	0.729	0	0.02

The sources influencing the overload of the indicated lines, demonstrated using the DC method, are presented in Table 2.

The application of the method of tracking active power flows showed the lack of participation of the considered source in the power flow through overloaded lines. According to this method, the G-113 source is mainly responsible for the overload of the 110 kV line 113–17, while the G-73 and G-24 sources are mainly responsible for the overload of the 23–24 line. The DC method

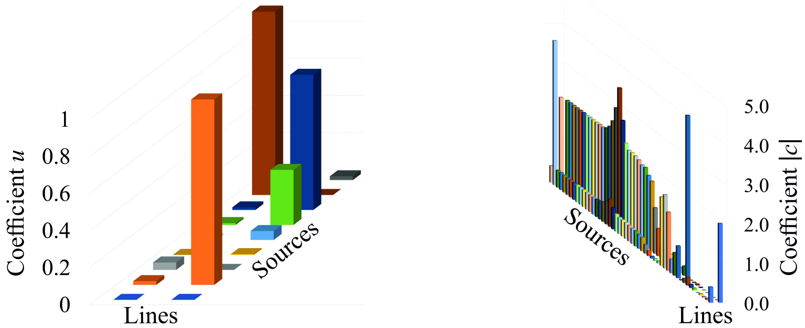
Table 2. List of overloaded lines along with the shares of individual sources responsible for them, according to the DC method (the participation rates were calculated according to Eq. (16)

Source	**Line overloaded**		**Source**	**Line overloaded**		**Source**	**Line overloaded**	
	113–17	**24–23**		**113–17**	**24–23**		**113–17**	**24–23**
G-55	**0.393**	**2.004**	G-36	0.054	0.293			
G-01	0.042	0.001	G-37	0.050	0.264	G-76	0.462	2.353
G-04	0.025	0.000	G-40	0.135	0.695	G-77	0.442	2.250
G-06	0.034	0.001	G-42	0.227	1.161	G-80	0.434	2.208
G-08	0.000	0.000	G-46	0.348	1.773	G-87	0.435	2.216
G-12	0.054	0.002	G-49	0.364	1.854	G-89	0.434	2.210
G-15	0.086	0.012	G-54	0.392	1.995	G-90	0.434	2.209
G-17	0.204	0.033	G-56	0.392	1.996	G-92	0.434	2.208
G-18	0.114	0.014	G-59	0.405	2.063	G-99	0.431	2.192
G-19	0.025	0.004	G-62	0.412	2.100	G-100	0.432	2.202
G-24	0.812	4.122	G-65	0.417	2.122	G-103	0.432	2.201
G-25	0.581	0.238	G-66	0.416	2.118	G-104	0.432	2.201
G-26	0.355	0.142	G-69	0.439	2.235	G-105	0.432	2.201
G-27	1.484	0.261	G-70	0.541	2.751	G-107	0.432	2.200
G-31	1.862	0.173	G-72	0.692	3.515	G-110	0.432	2.201
G-32	1.745	0.291	G-73	0.580	2.947	G-113	3.657	0.112
G-34	0.056	0.307	G-74	0.502	2.551	G-116	0.424	2.157

showed that the impedance coefficient for the G-55 source, described by Eq. (16), is significant and amounts to 0.4 in the case of lines 113–17 and 2 for lines 23–24. This means that limiting the power generated to 6 MW in the considered source will eliminate the overload of lines 23–24 and limit the overload of lines 113–17 to the extremely low threshold value required by the DSO, (this will reduce the value of the current flowing on this line by approx. 10 A). In order not to curtail the power in the considered source, a change in the network configuration can be used to eliminate the overload of the two lines. This change involves switching off two 110 kV lines 23–32 and 23–25. If the operator allows such operations, the problem of overloading lines or transformers can be solved by dispatching activities.

The results obtained by both methods are therefore not consistent. The conclusion is that the method of tracking power flows shows which sources in a specific network operating state are responsible for the overload of a given line from the point of view of current power flows. The DC method, on the other hand, allows one to determine the share of a given source from the point of view of the network operation configuration. Any change in the power distribution in selected sources does not change the size of their impact (values of impedance coefficients) on the overloaded branches. They result mainly from the structure of the network. They also allow one to determine whether the planned location of the source connection is appropriate. They also make it easier to answer the question whether his work will not significantly deepen existing overloads or create new ones whose level is unacceptable. A change in the network structure may result in a change in the values of impedance coefficients. Therefore, in the event of line overloads in various emergency states, each of them should be considered separately.

Figure 3 (illustrating the influence of sources on line loads) shows the values of the coefficients determined by both methods.



(a) (b)

Fig. 3. Values of coefficients showing the influence of sources on line loads: (a) power flow tracking method; (b) DC method

A similar impact can be observed in the case of connecting a new source, e.g. in nodes 62, 110 or 92 (Fig. 2), or increasing the power of sources existing in these nodes by 30 MW. The method of tracking power flows shows their insignificant impact on the overload of 110 kV lines 113–17 and 23–24. The coefficients determined by the DC method range from 0.4–0.43 for lines 113–17 and from 2 to 2.2 for lines 23–24. Connecting a source of the same power to nodes 1, 12, 15 and 36 (Fig. 2) was also considered. It was observed that their impact is much smaller in the case of lines 23–24 and there are no grounds to refuse the connection conditions.

4.3. Case 2

In the second step, a 360 MW source was connected at 400 kV node number 116 (Fig. 4). During the N-1 analysis in the system with the considered source, the shutdown of the 400 kV line 65–64 resulted in an overload of the 110 kV line 23–24 by 41.6% and the 110 kV line 5–6 by 7.6%, marked in bold purple line in Fig. 4. The sources responsible for the overload of the indicated lines, identified using the power flow tracking method, are included in Table 3.

The sources influencing the overload of the indicated lines, demonstrated using the DC method, are presented in Table 4.

Figure 5 (illustrating the influence of sources on line loads) shows the values of the coefficients determined by both methods.

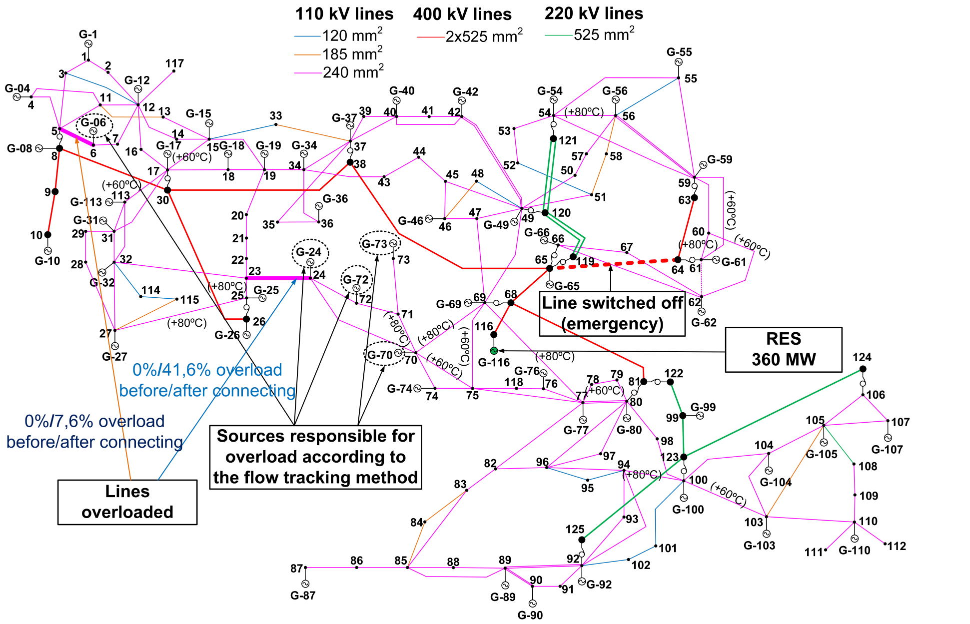


Fig. 4. Diagram of the IEEE 118-bus network with a marked 360 MW source connected at node 116 and disconnected by the 400 kV line 65–64

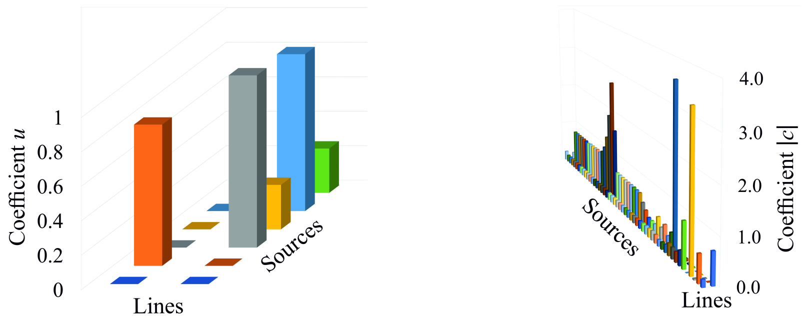
Table 3. List of overloaded lines along with the shares of individual sources responsible for them, according to the power flow tracking method (the participation coefficients were calculated according to Eq. (4)

Line overloaded	**Source**					
	G-116	G-06	G-24	G-70	G-72	G-73
From 6 to 5	**0**	0.82	0	0	0	0
From 24 to 23	**0**	0	1	0.258	0.911	0.257

However, the application of the active power flow tracking method showed the lack of participation of the considered source (G-116) in the power flow on overloaded lines. According to this method, the G-06 source is mainly responsible for the overload of the 110 kV line 5–6, while the G-24, G-70, G-72 and G-73 sources are mainly responsible for the overload of the 23–24 line. The DC method showed that the impedance coefficient for the G-116 source, described by Eq. (16), is significant and amounts to 0.165 in the case of lines 5–6 and 0.709 for lines 23–24. This means that limiting the power generated to 195 MW in the considered source will eliminate overload of both lines. In order not to limit the power in the considered source, a change in the network configuration can be made to eliminate the overload of the two lines. This change involves switching off three 110 kV lines 23–24 and 12–16. If the operator allows such operations, the problem of overloading lines or transformers can be solved by dispatching activities. Assuming

Table 4. List of overloaded lines along with the shares of individual sources responsible for them, according to the DC method (the participation coefficients were calculated according to Eq. (16)

Source	**Line overloaded**		**Source**	**Line overloaded**		**Source**	**Line overloaded**	
	6–5	**24–23**		**6–5**	**24–23**		**6–5**	**24–23**
G-116	**0.165**	**0.709**						
G-01	0.613	0.013	G-36	0.187	0.216	G-74	0.168	1.318
G-04	0.032	0.008	G-37	0.179	0.226	G-76	0.167	1.021
G-06	3.392	0.011	G-40	0.176	0.334	G-77	0.166	0.864
G-08	0.000	0.000	G-42	0.173	0.451	G-80	0.165	0.794
G-12	1.011	0.017	G-46	0.169	0.618	G-87	0.165	0.807
G-15	0.329	0.028	G-49	0.168	0.625	G-89	0.165	0.797
G-17	0.234	0.062	G-54	0.166	0.632	G-90	0.165	0.796
G-18	0.256	0.060	G-55	0.166	0.632	G-92	0.165	0.793
G-19	0.277	0.058	G-56	0.166	0.632	G-99	0.165	0.767
G-24	0.181	3.601	G-59	0.166	0.634	G-100	0.165	0.783
G-25	0.161	0.348	G-61	0.166	0.636	G-103	0.165	0.782
G-26	0.149	0.206	G-62	0.165	0.636	G-104	0.165	0.782
G-27	0.193	0.388	G-66	0.164	0.640	G-105	0.165	0.781
G-31	0.214	0.263	G-70	0.170	1.611	G-107	0.165	0.781
G-32	0.200	0.434	G-72	0.176	2.720	G-110	0.165	0.782
G-34	0.191	0.211	G-73	0.172	1.896	G-113	0.223	0.176



(a) (b)

Fig. 5. Values of coefficients showing the influence of sources on line loads: (a) power flow tracking method; (b) DC method

that the number of additional shutdowns cannot be greater than, for example, 3, you can look for configurations that will allow one to eliminate the resulting overloads without having to limit the power in the analysed source(s). The results obtained by both methods are also not consistent in this case. As previously mentioned, both methods indicate the influence of sources on the congestion of the indicated lines from a different point of view.

4.4. Case 3

In the third step, a 400 MW source was connected at 400/110 kV station number 64 (Fig. 6). During the N-1 analysis in the system with the considered source, switching off the 400 kV lines 30–38 resulted in an overload of 12 110 kV lines, marked with a bold purple line in Fig. 6.

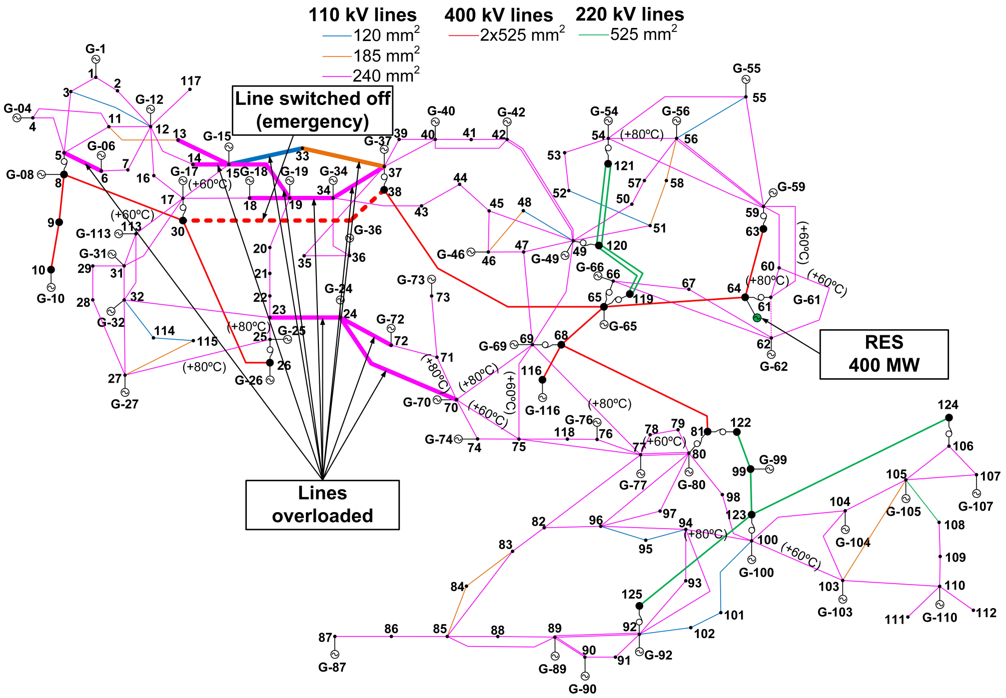


Fig. 6. Diagram of the IEEE 118-bus network with a marked 400 MW source connected at node 64 and disconnected by the 400 kV line 30–38

Overloaded lines along with the overload values, i.e. above 100% of the permissible current carrying capacity, are included in Table 5.

The sources responsible for the overload of the indicated lines, demonstrated using the power flow tracking method, are included in Table 6.

The sources influencing the overload of the indicated lines, shown using the DC method, are presented in Table 7.

Table 5. List of overloaded lines with overload values, % (before/after connecting source)

Overload	**Line overloaded (from-to)**											
	6–5	**15–13**	**15–14**	**19-15**	**33–15**	**19–18**	**34–19**	**24–23**	**70–24**	**72–24**	**37–33**	**37–34**
Before connecting	0	0	0	0	0	0	0	0	0	0	0	0
After connecting	14	4.8	3.3	23.7	257	15.3	143	160	12.8	17.2	191	78.4

Table 6. List of overloaded lines along with the shares of individual sources responsible for them, according to the power flow tracking method (the participation coefficients were calculated according to Eq. (4)

Source	**Line overloaded (from-to)**											
	6-5	**15-13**	**15-14**	**19-15**	**33-15**	**19-18**	**34-19**	**24-23**	**70-24**	**72-24**	**37-33**	**37-34**
G-64	**0.00**	**0.06**	**0.06**	**0.06**	**0.13**	**0.06**	**0.13**	**0.14**	**0.11**	**0.03**	**0.15**	**0.11**
G-06	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G-19	0.00	0.16	0.15	0.49	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.00
G-34	0.00	0.16	0.15	0.49	0.00	0.45	1.00	0.00	0.00	0.00	0.00	0.00
G-36	0.00	0.16	0.15	0.49	0.00	0.45	1.00	0.00	0.00	0.00	0.00	0.00
G-37	0.00	0.20	0.20	0.22	0.43	0.20	0.44	0.00	0.00	0.00	0.50	0.38
G-40	0.00	0.14	0.14	0.15	0.30	0.14	0.31	0.00	0.00	0.00	0.35	0.26
G-42	0.00	0.07	0.07	0.08	0.15	0.07	0.16	0.00	0.00	0.00	0.18	0.14
G-46	0.00	0.01	0.01	0.04	0.00	0.04	0.08	0.00	0.00	0.00	0.00	0.00
G-49	0.00	0.01	0.01	0.02	0.01	0.02	0.05	0.08	0.06	0.02	0.01	0.01
G-54	0.00	0.01	0.01	0.02	0.02	0.02	0.04	0.06	0.05	0.01	0.02	0.02
G-55	0.00	0.01	0.01	0.02	0.02	0.02	0.03	0.05	0.04	0.01	0.02	0.02
G-56	0.00	0.01	0.01	0.01	0.01	0.01	0.03	0.04	0.03	0.01	0.01	0.01
G-62	0.00	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.00	0.02	0.06
G-24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
G-70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.79	0.21	0.00	0.00
G-72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00
G-73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99	0.00	0.99	0.00	0.00

Table 7. List of overloaded lines along with the shares of individual sources responsible for them, according to the DC method (the participation coefficients were calculated according to Eq. (16)

Source	Line overloaded (from-to)											
	6-5	**15-13**	**15-14**	**19-15**	**33-15**	**19-18**	**34-19**	**24-23**	**70-24**	**72-24**	**37-33**	**37-34**
G-64	**0.30**	**0.54**	**0.58**	**0.75**	**1.74**	**0.94**	**1.71**	**1.80**	**1.01**	**0.79**	**1.74**	**1.10**
G-01	0.62	0.22	0.47	0.19	0.05	0.13	0.01	0.06	0.03	0.03	0.05	0.00
G-04	0.04	0.28	0.22	0.13	0.03	0.10	0.01	0.04	0.02	0.02	0.03	0.00
G-06	3.40	0.20	0.37	0.16	0.04	0.11	0.01	0.05	0.03	0.02	0.04	0.00
G-08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
G-12	1.02	0.24	0.62	0.24	0.06	0.16	0.01	0.07	0.04	0.03	0.06	0.00
G-15	0.36	0.73	0.79	0.98	0.23	0.74	0.02	0.26	0.14	0.11	0.23	0.00
G-17	0.25	0.32	0.32	0.12	0.00	0.19	0.03	0.03	0.02	0.02	0.00	0.02
G-18	0.28	0.45	0.47	1.35	0.07	1.84	0.24	0.16	0.09	0.07	0.07	0.17
G-19	0.32	0.58	0.62	2.58	0.15	1.77	0.44	0.29	0.16	0.13	0.15	0.32
G-24	0.23	0.38	0.40	0.59	0.64	0.45	0.55	4.06	0.67	0.53	0.64	0.35
G-25	0.17	0.25	0.25	0.28	0.15	0.08	0.10	0.25	0.14	0.11	0.15	0.06
G-26	0.16	0.22	0.22	0.20	0.10	0.02	0.06	0.16	0.09	0.07	0.10	0.04
G-27	0.21	0.30	0.30	0.29	0.15	0.05	0.10	0.25	0.14	0.11	0.15	0.06
G-31	0.23	0.31	0.32	0.23	0.09	0.05	0.04	0.13	0.07	0.06	0.09	0.03
G-32	0.22	0.31	0.32	0.32	0.17	0.06	0.11	0.27	0.15	0.12	0.17	0.06
G-34	0.31	0.57	0.62	0.99	1.74	1.12	2.26	1.25	0.70	0.55	1.74	2.20
G-36	0.31	0.57	0.62	0.92	1.82	1.09	2.14	1.29	0.72	0.57	1.82	1.00
G-37	0.31	0.58	0.62	0.77	1.98	1.03	1.91	1.36	0.76	0.60	1.98	1.54
G-40	0.31	0.57	0.61	0.77	1.92	1.01	1.86	1.47	0.82	0.65	1.92	1.38
G-42	0.30	0.56	0.60	0.77	1.85	0.99	1.81	1.59	0.89	0.70	1.85	1.21
G-46	0.30	0.55	0.58	0.78	1.74	0.96	1.77	1.74	0.98	0.77	1.74	0.72
G-49	0.30	0.54	0.58	0.77	1.75	0.95	1.74	1.76	0.99	0.78	1.75	0.95
G-54	0.30	0.54	0.58	0.76	1.75	0.95	1.72	1.78	1.00	0.78	1.75	1.04
G-55	0.30	0.54	0.58	0.76	1.74	0.95	1.72	1.78	1.00	0.79	1.74	1.04
G-56	0.30	0.54	0.58	0.76	1.75	0.95	1.72	1.78	1.00	0.78	1.75	1.04
G-59	0.30	0.54	0.58	0.76	1.74	0.95	1.71	1.79	1.00	0.79	1.74	1.07

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Source	Line overloaded (from-to)											
	6-5	**15-13**	**15-14**	**19-15**	**33-15**	**19-18**	**34-19**	**24-23**	**70-24**	**72-24**	**37-33**	**37-34**
G-62	0.30	0.54	0.58	0.75	1.74	0.94	1.71	1.80	1.01	0.79	1.74	1.10
G-66	0.30	0.54	0.58	0.75	1.74	0.94	1.71	1.80	1.01	0.79	1.74	1.11
G-70	0.28	0.49	0.52	0.70	1.38	0.78	1.33	2.54	1.42	1.12	1.38	0.84
G-72	0.25	0.43	0.45	0.64	0.97	0.60	0.90	3.38	0.26	3.13	0.97	0.56
G-73	0.27	0.47	0.50	0.68	1.27	0.74	1.22	2.75	1.12	1.63	1.27	0.77
G-74	0.28	0.51	0.54	0.72	1.49	0.83	1.45	2.31	1.30	1.02	1.49	0.91
G-76	0.29	0.52	0.56	0.73	1.60	0.88	1.56	2.09	1.17	0.92	1.60	0.99
G-77	0.29	0.53	0.57	0.74	1.66	0.91	1.62	1.97	1.10	0.87	1.66	1.03
G-80	0.29	0.53	0.57	0.75	1.69	0.92	1.65	1.92	1.07	0.84	1.69	1.06
G-87	0.29	0.53	0.57	0.75	1.68	0.92	1.64	1.93	1.08	0.85	1.68	1.05
G-89	0.29	0.53	0.57	0.75	1.68	0.92	1.65	1.92	1.07	0.84	1.68	1.06
G-90	0.29	0.53	0.57	0.75	1.68	0.92	1.65	1.92	1.07	0.84	1.68	1.06
G-92	0.29	0.53	0.57	0.75	1.69	0.92	1.65	1.91	1.07	0.84	1.69	1.06
G-99	0.29	0.54	0.57	0.75	1.70	0.92	1.66	1.89	1.06	0.83	1.70	1.06
G-100	0.29	0.53	0.57	0.75	1.69	0.92	1.65	1.91	1.07	0.84	1.69	1.06
G-103	0.29	0.53	0.57	0.75	1.69	0.92	1.65	1.91	1.07	0.84	1.69	1.06
G-104	0.29	0.53	0.57	0.75	1.69	0.92	1.65	1.91	1.07	0.84	1.69	1.06
G-105	0.29	0.53	0.57	0.75	1.69	0.92	1.65	1.91	1.07	0.84	1.69	1.06
G-107	0.29	0.54	0.57	0.75	1.69	0.92	1.65	1.91	1.07	0.84	1.69	1.06
G-110	0.29	0.53	0.57	0.75	1.69	0.92	1.65	1.91	1.07	0.84	1.69	1.06
G-113	0.24	0.32	0.32	0.18	0.05	0.11	0.01	0.06	0.03	0.03	0.05	0.00

Figure 7 (illustrating the influence of sources on line loads) shows the values of the coefficients determined by both methods.

The application of the active power flow tracking method showed small shares of the considered source (G-64) in the power flow on overloaded lines, which is presented in Table 8. These shares are not significant because they range from 0 to 0.131 (depending on the overloaded line). However, the DC method showed that the impedance coefficients for the G-64 source, described by Eq. (16), are significant in some cases of overloaded lines, as shown in Table 7. Table 7 shows that the least sensitive lines are the 110 kV lines of the 15–13, 15–14. None of the impedance coefficients described by Eq. (16) is greater than one. This means that a change in generation by 1 MW in any source will result in a change in the current value in these lines by less than 1 A. The remaining lines are characterised by greater sensitivity ($|c| > 1$ coefficients). In order to relieve the load on

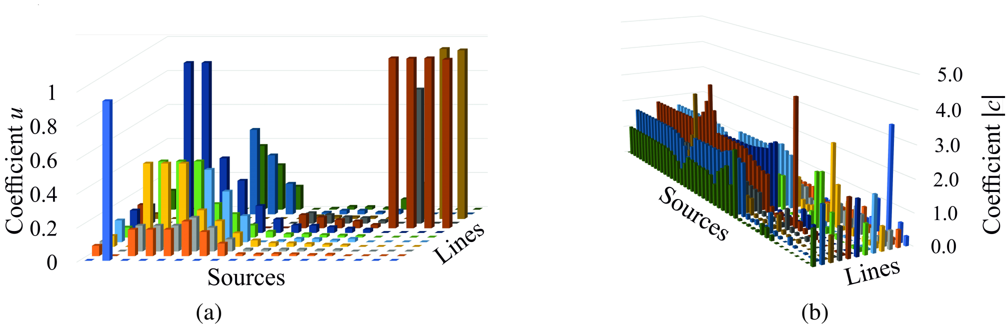

Fig. 7. Values of coefficients showing the influence of sources on line loads: (a) power flow tracking method; (b) DC method

all twelve overloaded lines, it is necessary to curtail the G-64 generator output to 63 MW (the resultant curtailment is equal to 400 − 63 = 337 MW). In this case, it is not possible to find a network configuration that would eliminate the overload of twelve lines. It is therefore necessary to redispatch power generated in the considered source between other units. Another solution is to optimally reduce the output power of the sources that most affect overloads, selected according to the method of power tracking.

The objective function (F_{obj}) in this task is the total value of power generated (P_{g}) in the sources presented in Table 6, described by the following relationship:

$$F_{\mathrm{obj}} = \sum_{j=1}^{n} P_{\mathrm{g}j}, \tag{19}$$

where n is the number of sources that constitute decision variables.

The considered objective function (F_{obj}) is subject to maximization. We are looking for such a power distribution in selected sources that will eliminate the resulting line overloads. The task is therefore to minimize the power reduction in the sources. The limitations are the permissible values of line current carrying capacity, permissible voltage values at nodes, power balance, as well as limitations related to the maximum and minimum values of power generated in sources.

Table 8 shows the results obtained in the optimization process. To solve the optimization task, one of the Cuckoo Search metaheuristic optimization methods was used. The results were achieved for the following cases:

– the reduction of power generated P_{g} in the sources considered is covered only by the source connected in the balancing node (state marked as 1 in Table 8),
– the reduction of power generated P_{g} in the sources considered is covered by other sources not participating in the optimization process (state marked as 2 in Table 8).

The obtained results allow us to conclude that:

– if the imbalance is covered only by the balancing node, then the total power curtailment will be 321 MW,
– if the imbalance is covered by other sources in the system, then the total power curtailment will be 234 MW.

Table 8. List of sources involved in the optimization process along with optimal power values P_{gopt1} and P_{gopt2}

Source	P_g	P_{gopt1}	P_g–P_{gopt1}	P_{gopt2}	P_g–P_{gopt2}
	MW	**MW**	MW	**MW**	MW
G-64	**400**	**383**	**17**	**400**	**0**
G-06	100	100	0	100	0
G-19	40	40	0	40	0
G-34	50	50	0	49	1
G-36	20	7	13	20	0
G-37	136	37	99	0	136
G-40	40	29	11	33	7
G-42	60	6	54	48	12
G-46	20	6	14	11	9
G-49	50	45	5	20	30
G-54	150	142	8	149	1
G-55	100	99	1	100	0
G-56	100	90	10	100	0
G-62	100	51	49	83	17
G-24	20	14	6	12	8
G-70	60	33	27	58	2
G-72	25	24	1	25	0
G-73	30	24	6	19	11
Sum	1501	1180	321	1267	234

The applied optimization, in addition to effectively eliminating line overloads, also allows one to determine which sources, among those previously selected, significantly affect the condition of overloaded lines. This knowledge also makes it possible to select the minimum number of sources to perform the power redistribution procedure, and thus minimizes the costs of this operation. The power generated by the considered G-64 source is limited by 17 MW in the first case, while in the second case there is no need to limit its power.

When it comes to the most attractive connection points for new sources, these are nodes no. 1, 4, 8, 15, 17, 25, 26, 27, 31, 32, 113. Connecting the source in these nodes and with this network configuration will have the least impact on the overload of the indicated lines.

Comparing both methods, it should be said that:

– the power flow tracking method is more effective in eliminating line overloads online, it allows you to select all sources that currently affect line overloads, it also allows you to identify those sources whose impact is the greatest, the results obtained using it (share factors for sources) strongly depend on the current load, generation, location of sources and loads, power losses, voltages in nodes and network configuration;

– the DC method is more effective at the stage of planning and searching for a source connection site, it allows examining the impact of its connection on the line load from the point of view of the network structure and its configuration, the results obtained using it may be useful for investors in making decisions about the connection location, the source share coefficients determined based on this method do not depend on the current load and generation, but they allow one to deduce how significant the impact of connecting the source in the considered node will be on the line overloading.

The results obtained by both methods are therefore convergent because they indicate the contribution of the considered source to the overloading of the indicated lines. As previously mentioned, both methods indicate the influence of the source from a different point of view, as evidenced by its share coefficients for individual lines.

5. Summary

The article presents an extremely important problem of thermal overloading of existing 110 kV power lines that occurs in Poland, in analyses related to examining the impact on the power system of renewable energy sources or energy storage facilities planned for connection. Operators often refuse to sign connection agreements for these facilities when their impact on line overloads or the worsening of existing overloads is greater than the threshold value. The article uses the method of tracking active power flows and the DC method to select those sources that have a significant impact on the formation of line current overloads or the deepening of existing overloads on power lines. Both methods are different. The method of tracking active power flows allows one to identify all sources whose generation affects the total load on the power line. Therefore, this is the method that is most suitable for making decisions regarding the selection of the composition of generating units causing line overload in a given network operating condition. By combining it with optimisation methods, it is possible to determine the optimal distribution of generation which allows one to eliminate thermal overloads. The DC method allows one to identify all nodes for which connecting of the planned source may significantly affect the load on power lines. It can be used to indicate those nodes that are most attractive for the investors. Both methods are sensitive methods that allow one to look at the problem of line overload from a different perspective. The tracking method is more computationally accurate because it indirectly takes into account reactive power flows in the calculations. The DC method does not take into account reactive power in flows; therefore, it is sometimes quite a significant simplification. Therefore, the results obtained using it should be verified using other methods.

Various works can be found in the literature (e.g. [2–6]) on sensitivity analysis in the power system. Generally, they are used to determine the effect of changes in one quantity on changes in another quantity. Therefore, the relationship between various variables is sought. Each method is valuable because it has specific advantages and properties that can be used to solve selected problems. This article uses and compares both due to their practical importance. As mentioned earlier, both methods may lead to different conclusions. They allow you to look at the issue of line congestion from a different perspective. They indicate which factors influence overload. They enable the analysis of overloads from various points of view. They can be used both at the planning and operational stages of the grid.

The originality of the approach presented in the article results from the use of two different sensitivity methods, allowing the selection of energy sources/storages that have a significant impact on current overloads of power lines. The literature lacks this type of analysis that could be used to solve an extremely important problem currently faced by both power grid operators and potential investors. The novelty of the proposed method, in relation to other works found in the literature, is also manifested in its simplicity, high effectiveness and possibility of application in practice. The implementation of the proposed algorithms is relatively easy and the effects that can be achieved are very large both from the point of view of the network operator and potential investors. The need to perform such calculations results from the practice of the authors, who notice signals coming from entrepreneurs who sometimes have very big problems in obtaining connection conditions for the RES sources planned to be connected. New investors who plan to connect a source to the power grid expect such analyses to be able to make business decisions related to the choice of the place to connect the source and the maximum value of its connection power. Having information about the available connection capacities for sources in the considered network area, and knowing the investment consequences resulting from connecting the planned facilities to the network, investors can more easily make decisions related to the selection of the location for the source. The choice of the connection site does not only result from the location of an attractive area, but also from technical analyses determining the connection power and the profitability of the investment.

As part of further work on the presented problem, the authors also plan to use selected methods based on artificial intelligence and correlation coefficients. The results obtained using these methods will be obtained much faster, which will allow decisions to be made practically in real time. With such a tool, operators will be able to provide accurate information on the current and prospective hosting capacity of the grid.

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