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THE USE OF DIFFERENTIAL EVOLUTION TO DETERMINE MAXIMUM GENERATION AND LOAD VALUES IN THE DISTRIBUTION NETWORK

UPORABA DIFERENČNE EVOLUCIJE ZA DOLOČITEV NAJVEČJE PROIZVODNJE TER PORABE V DISTRIBUCIJSKEM OMREŽJU

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Keywords: distribution network, renewable energy sources, optimisation method, voltage profile

Abstract

By integrating renewable energy sources into the existing distribution network, the characteristics and local stability of the network is highly impacted. The network, which was built with the goal of a directed energy flow from large conventional sources connected to the transmission network via the distribution network to consumers, can change the direction of the energy flow. The adoption of environmental commitments and directives encourages the integration of local dispersed energy sources, which can worsen voltage conditions in the distribution network. To avoid excessive local production, distribution network operators must limit the installation of

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new generation units, as it is necessary to take into account the quality of power supply by monitoring its network parameters, such as the appropriate voltage profile and the ratio between active and reactive power. On the other hand, excessive loads due to the mass transition of household heating and transport towards electricity can also pose a problem for high-quality electricity supply due to the excessive voltage drop. The article presents an algorithm for determining the maximum size of unit production and the maximum load at a node in the distribution network. Also demonstrated is the use of variable tap transformer technology, which adjusts the tap of the transformer to provide an appropriate voltage profile in the network. The entire analysis was performed on a model of a real medium-voltage network, in which solar and hydropower plants are already included. The model was verified by comparing its calculated values with actual measurements. The goal was to determine the size of the unit's maximum production, as well as the size of the maximum load, by using the differential evolution algorithm, while keeping voltage profiles within the permissible limits. The results of the analysis are presented in the article.

Povzetek

Z vključevanjem obnovljivih virov energije v obstoječe distribucijsko omrežje vplivamo na karakteristike in lokalno stabilnost omrežja. Omrežje, ki je bilo zgrajeno s ciljem usmerjenega pretoka energije od velikih konvencionalnih virov, priklopljenih na prenosno omrežje preko distribucijskega omrežja do porabnikov, lahko spreminja usmerjenost pretoka energije. Sprejetje okoljskih zavez in direktiv spodbuja integracijo lokalnih razpršenih virov energije, ki lahko poslabša napetostne razmere v distribucijskem omrežju. V izogib čezmerni lokalni proizvodnji želijo operaterji distribucijskih omrežij omejiti priklapljanje novih proizvodnih enot, saj je treba upoštevati kakovostno oskrbo s spremljanjem parametrov omrežja, kot sta ustrezen napetostni profil ter razmerje med delovno in jalovo močjo. Prevelika bremena pa zaradi množičnega prehoda ogrevanja in transporta na električno energijo prav tako prestavljajo težavo za kakovostno oskrbo z električno energijo. V članku je predstavljen algoritem za določitev največje velikosti proizvodnje enote in največjega bremena v vozlišču v distribucijskem omrežju. Prikazana je tudi uporaba tehnologije transformatorja s spremenljivo prestavo, ki prilagodi prestavo transformatorja tako, da zagotovi ustrezen napetostni profil v omrežju. Celotna analiza je bila narejena na modelu realnega srednjenapetostnega omrežja, v katerega so že vključene sončne in hidroelektrarne. Model je bil verificiran tako, da smo izračunane vrednosti modela primerjali z dejanskimi meritvami. Cilj je določiti velikosti maksimalne proizvodnje enote in bremena z uporabo algoritma diferenčne evolucije, pri tem pa ohraniti napetostne razmere znotraj dopustnih meja. V članku so predstavljeni rezultati opravljene analize.

1 INTRODUCTION

With the development of dispersed sources of production and environmental protection commitments, the distribution network has undergone a major transformation in recent years. If in the past it was considered a passive part of the power grid with a consumer character, with the integration of distributed sources it is turning into an active one. As a result of the change in network activity, new requirements for network operation and the need for advanced planning algorithms and optimisation of network operation arise. To analyse operating conditions and energy flows in the network, it was necessary to develop appropriate models that describe conditions in the network. These algorithms need to be adapted, since distribution networks are mostly radial in nature, while transmission networks are closed-looped. By including distributed sources and larger loads in the distribution network, the voltage profiles are heavily influenced. The main problem with distributed sources of electricity is that the production of electricity depends on meteorological conditions and/or the time of day. Due to unreliable and unpredictable current production from scattered sources, it is difficult to coordinate current consumption. Therefore, local power surges may occur in the network, where voltages in the lines may exceed the permissible values in the case of excessive production, and at the same time voltages may drop sharply below the permissible value in the case of excessive loads. Adequate voltage conditions can be ensured by several methods and measures, such as: changing the topology of the network or even by replacing conductors with ones of larger cross-sections. These measures are passive, usually very expensive and sometimes not the most optimal; sometimes the optimal placement of distributed resources in the network is sufficient.

Chapter 2 presents the creation of the network model and verification; Chapter 3 presents the results of the analysis. The analysis is divided into several parts: the first part consists of the analysis of the current situation in the network, the second part consists of the analysis of determining the maximum production and the maximum load for a summer and winter day, and the third part consists of the introduction of OLTC, when we include production units in the network that cause an increase in voltage in a network that is larger than allowed. Chapter 4 presents the conclusion.

2 DESCRIPTION OF METHODS AND MODEL VERIFICATION

The article discusses a practical example of the operation of a radial medium-voltage distribution line. Data about the network topology and the parameters of the network elements were obtained from the distribution company. The data was processed as shown in Figure 1, where the original *shp* data is converted to *Excel* using the *Qgis* program and imported into the *Matlab* environment, where all further network analysis and later optimisations are carried out.

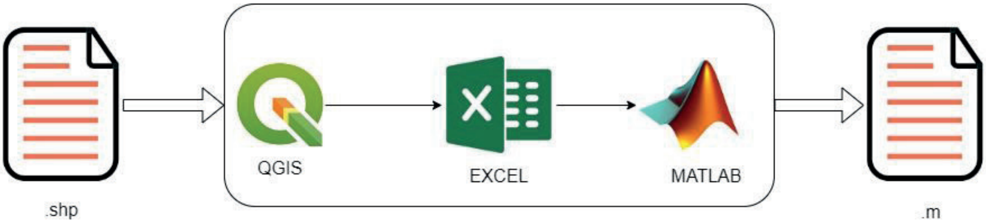

Figure 1: *Conversion of data from the distribution operator into a structure for resolving electrical networks*

To create the network model, a *Matlab* environment was used, where a network model for the calculation of voltage conditions for the planned topology and parameters of the lines was created. The model of the considered network with thirty-six nodes is shown symbolically in Figure 2, where nodes in which solar or hydro power plants already connected are marked in red. For the purposes of the analysis, any node could be changed arbitrarily.

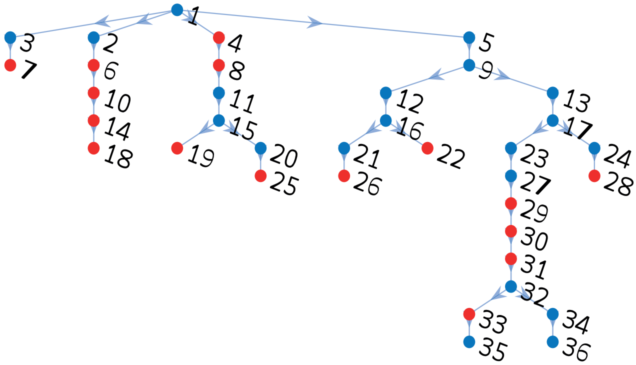

Figure 2: *Renumbered topology of considered radial distribution network*

The three solar power plants (PV) and five hydroelectric power plants (HPP) are included in the network. Data on the nominal generated power P_{gen} and the type of individual production of the unit are shown in Table 1.

Table 1: *Rated power and type of power plant included in the specific node*

	Node	P_{gen} [kW]	Type
TP 1	30	22	PV
TP 2	31	0	/
TP 3	14	276	HPP
TP 4	35	11	PV
TP 5	10	169	HPP
TP 6	26	1316	HPP
TP 7	18	287	HPP
TP 8	7	0	/
TP 9	4	160	HPP
TP 10	8	0	/
TP 11	25	207	HPP
TP 12	6	49	PV
TP 13	19	205	HPP
TP 14	29	0	/
TP 15	22	0	/
TP 16	28	0	/

The created network model, which has been built, was also verified before further analysis. Several types of load flow methods are known [2,3,5], but in this case the BFS algorithm has been used [1]. Verification of the calculation was carried out by calculating on an arbitrary day and at any measurement point, where the two years of measurement data were available with ninety-six measurement samples per day at 15-minute time intervals, therefore giving over 70,000 measurement points in total. The goal of verification is to check the accuracy of the calculation of the built model by comparing the results with measurements.

In Figure 3, a comparison for the selected day is presented, where a comparison between the measured voltage value and the calculated voltage values in each phase can be seen. A minor asymmetry is visible in phase $L1$, whilst in phases $L2$ and $L3$ correspondence with the measurements is satisfactory. Based on many selected currents and several days, we can conclude that the built model realistically describes the voltage situation and that it can be used for the study of potential new loads as well as new dispersed sources.

In Figure 3, on the left, it can be seen that the same P and Q values as were used for the measurements were used for the model calculation. The graph on the right shows the voltages, where it can be seen that in the case of phases $L1$ and $L2$ there is a relatively good match, while in phase $L3$ there is a smaller deviation, but this model cannot take this into account.

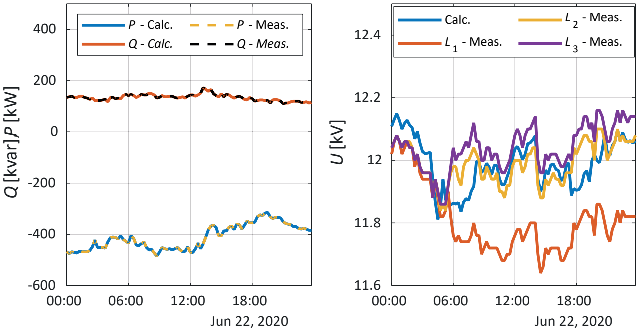

***Figure 3:** Comparison of calculations and measurements for selected day*

After the verification of the model, the next step was to utilise an optimisation, which is a process of finding the parameters of the function so that the final value of the function cannot be improved. This means that, using optimisation methods, the optimum that gives either the lowest or the highest function value was found. Several types of optimisation methods are known [4,6,7], but in this case the differential evolution algorithm has been used. The differential evolution flow chart is shown in Figure 4. The optimisation process starts with the generation of NP randomly selected vectors of dimension D. Then the following operations are performed: mutation, crossover and selection [8].

The optimisation seeks the minimum of the criterion function, which is defined as (2.1) in the case where only one parameter is sought:

$$q = \frac{1}{x_p(1)} + p \tag{2.1}$$

When two parameters are sought, the criterion function is written by (2.2), and similarly the optimisation can be extended to more parameters.

$$q = \left(\frac{1}{x_p(1)} + \frac{1}{x_p(2)}\right) + p \tag{2.2}$$

In the context of the discussed issue of adding production units or additional loads, let's say that in the first case we were only looking for a single-criteria optimisation using equation (1), and in the case of a dual-criteria optimisation using equation (2) we were simultaneously looking for P_L and P_G in different nodes. In both equations, the variable p represents penalties or penalty functions, which are designed in such a way that by including additional production or load, we do not exceed the voltage limits.

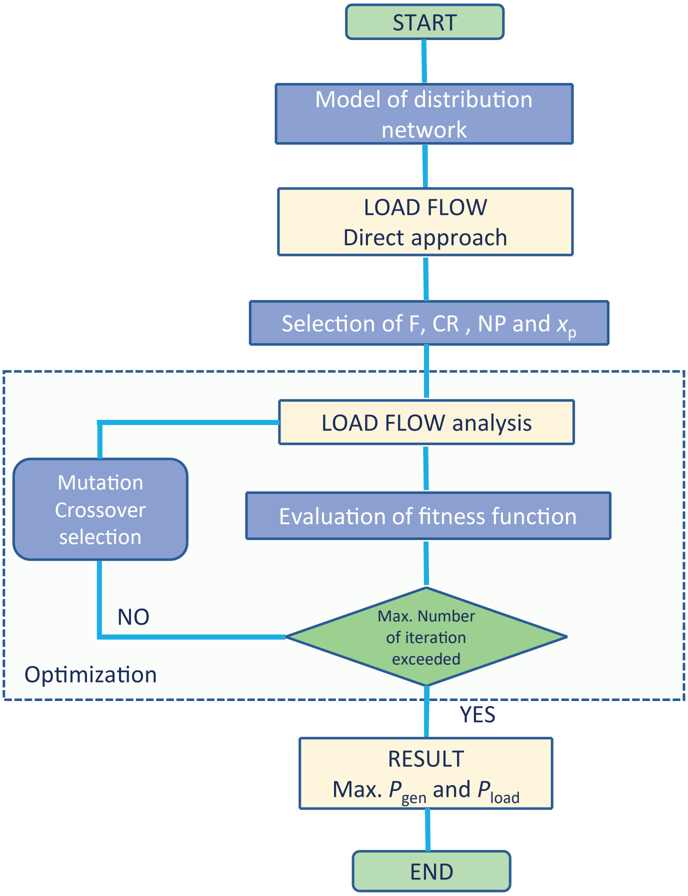

Figure 4: *Flowchart of the proposed procedure for the optimisation of network operation*

Voltage quality problems can occur in the network, meaning the voltage in the network is too low or too high. The permissible limits between which the voltage can fluctuate are prescribed in the SIST EN 50160 standard and are usually ±10%. There are several ways to solve the problems of too low or too high voltages. One possibility is to replace long-distance cable connections of smaller cross-sections with cables of larger cross-sections, change the network topology, and other such changes. Although these solutions are technically easy to implement and bring an additional benefit in terms of reduced electricity losses, they have a high investment cost. In the distribution network, voltage regulation is also possible using OLTC (On Load Tap Changer). A medium voltage/low voltage transformer with OLTC can have 9 taps and is able to regulate the voltage in steps of ±3%. The selected transformer can decrease or increase the voltage by a maximum of 12% of the nominal voltage [9].

3 RESULTS

On the built and verified model, the maximum network limits for adding new elements to any node of the network can be checked on the real network parameters.

3.1 Analysis of the current situation in the network

Figure 5 shows the analysis of non-zero load nodes. Six such nodes exist with a unique loading profile, with the largest load being in node 27. A similar analysis is also done for the production units for the selected day in January, where out of every thirty-five nodes, only seven are generating energy, the others being negligible. Figure 6 shows that some production units are independent of the time of day, considered as production from small hydropower plants, while production from solar power plants depends on the time of day.

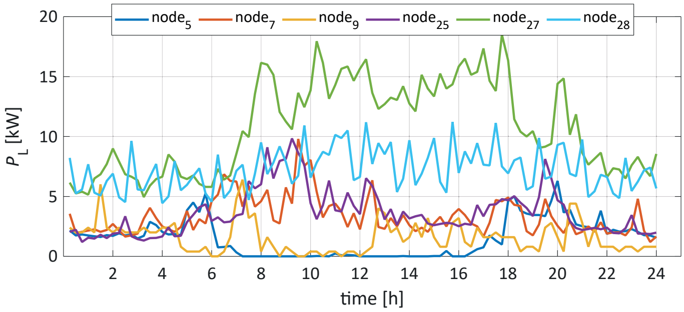

Figure 5: *Loading profile of selected nodes for a winter day, January 5th*

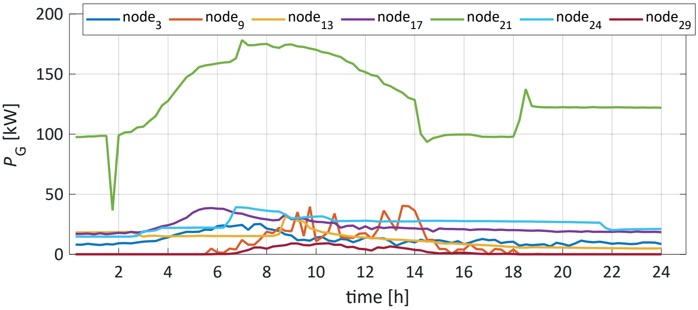

Figure 6: *Generation profile of selected nodes for a winter day, January 5th*

The analysis of voltage conditions does not change significantly over a single day in all 15-minute intervals, so the results for a working day of the year are presented for a selected part of the day, because the values deviate the most from the average profile. Figure 7 shows an analysis of the voltage profiles at an individual node, where either the minimum values or the maximum values for the month are presented. The highest voltage occurs in the month of February, while the lowest occurs in September. From this it can be concluded that for all 365 days and all ninety-six 15-minute interval measured values each day, only those of potential concern are plotted. Based on permissible voltage limits, it can be concluded that there are no problems with the voltage profile in the considered network. On the other hand, the effects of additional elements in the network can be analysed and their maximum values can be estimated so that the values are still within the prescribed limits.

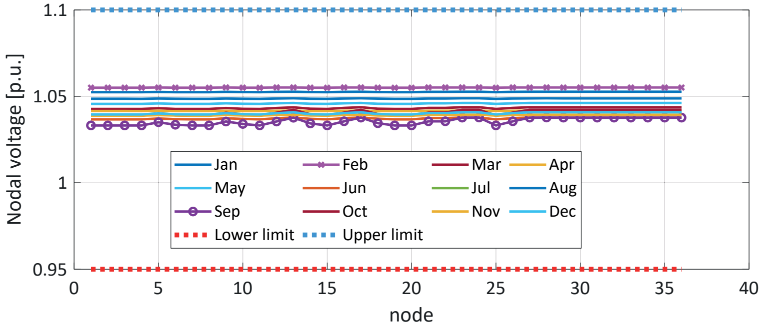

Figure 7: *Voltage profile throughout the year for a worst case scenario*

3.2 Determination of maximum load and maximum production unit

On the left in Figure 8, the voltage distribution when additional production units are added to the selected node 9 is shown. For the selected day and the selected moment of the day, a relatively large generating unit can be added to the node and at the same time the voltage profile is kept within the permissible limits of +10%. When the limit is exceeded, as in the case of +50 MW, the voltage in a larger number of nodes is exceeded, and nodes are immune to addition depending on the network topology. A similar analysis is made for adding loads to the node, as shown on the right in Figure 8. More than 80 MW of load can be added to node 9 without worsening the voltage profile, but in the case of 100 MW the values exceed the permissible limits.

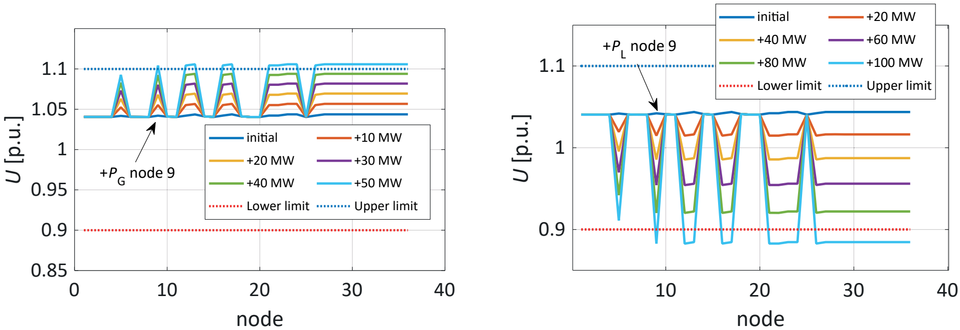

Figure 8: *Voltage profile in all thirty-five nodes while adding generation unit into node 9 (left) and adding load (right)*

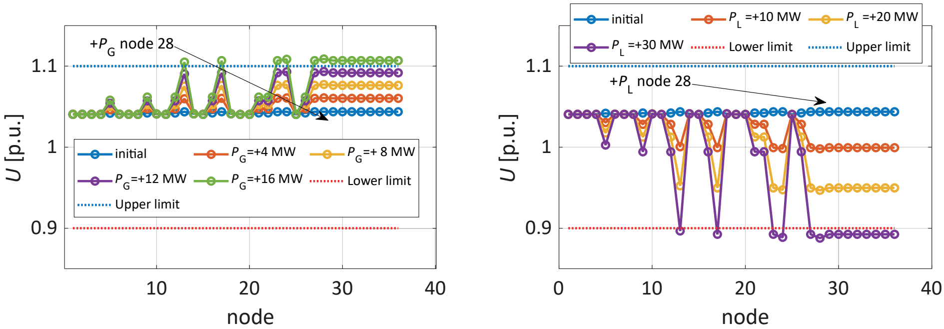

Figure 9: *Voltage profile in all thirty-five nodes while adding generation unit into node 28 (left) and adding load (right)*

A similar analysis can be performed for any node, as presented for the example of node 28 in Figure 9. The graph on the left shows that adding generating units again raises the voltage, and the limit is exceeded for the added 16 MW. It can also be observed that when adding loads, the voltage decreases, as shown in the graph on the right, where the limit is exceeded at an added load of 30 MW. In the rest of the article, the simultaneous addition of loads and generators is presented, but before that, an annual analysis of the situation in the network is presented.

As presented so far, changes to both loads and production are conducted manually, and only for the selected moment of the selected day. If the goal is to give a definitive answer about the maximum values of additional elements, it is necessary to perform a substantial number of calculations. It is simpler to use the optimisation algorithm from Figure 4, where calculations can be performed arbitrarily for each non-balance node.

On the left in Figure 10, the calculation of the maximum unit production for nodes 2 to 36 for both summer and winter days is shown. On the right-hand side, the calculation of the maximum load for nodes is shown. The calculation of the maximum production or load is calculated so that the voltage remains within the permissible limits. Since the network is radial, larger unit productions can be included at the beginning of the lines, and the closer we get to the nodes at the end of the lines, the smaller the calculated maximum unit production size is. The optimisation process is similar to the graphs in Figures 8 and 9, except that in a maximum of 50 iterations the result converges to the satisfactory value.

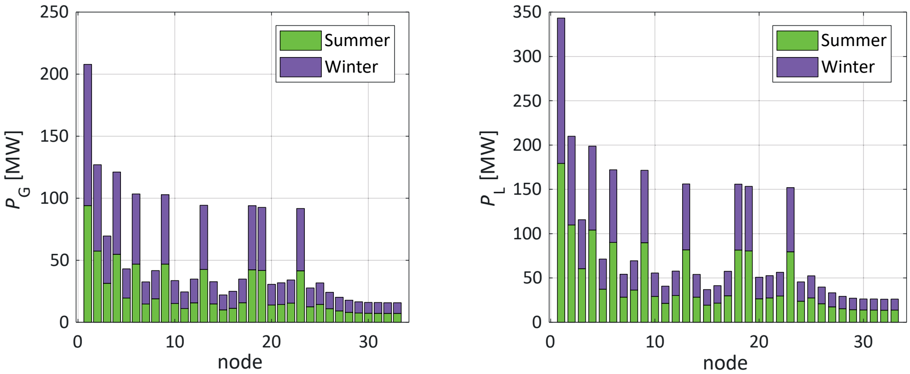

Figure 10: *Values of P_G and P_L for nodes 2 to 36 over two seasons*

However, we can conclude that the values calculated in the latter analysis are not necessarily final if the described OLTC device is installed in the network. The continuation presents an analysis of what can happen in the network when a production unit is connected to the network, which, due to its operation, causes the voltage to rise above the permitted limit. As many as two production units in nodes 21 and 22 are included in the network. Figure 11 displays the topography of the network, on which the location of the OLTC is visible (node 16, in red) and the nodes in which additional production units are added are marked with P_{gen}, node 21 and 22.

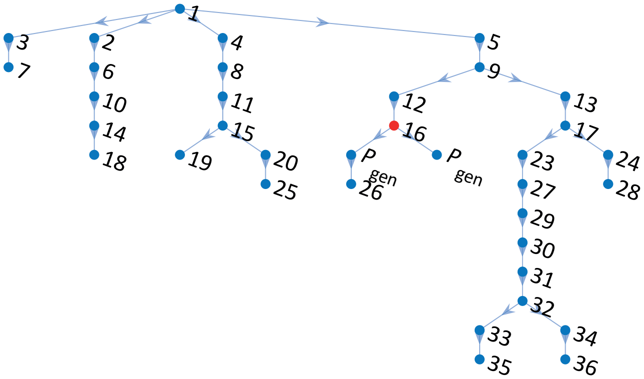

Figure 11: *Topology of considered radial distribution network with marked node with OLTC and nodes of additional generation units*

Figure 12a shows the additional production unit for node 21 over time. A 20 MW generating unit is connected to the grid, which operates at a constant power throughout the day, and at 11:00 a 20 MW generating unit is added to it. Figure 12b shows the same for node 22, except that the additional generating unit is connected later.

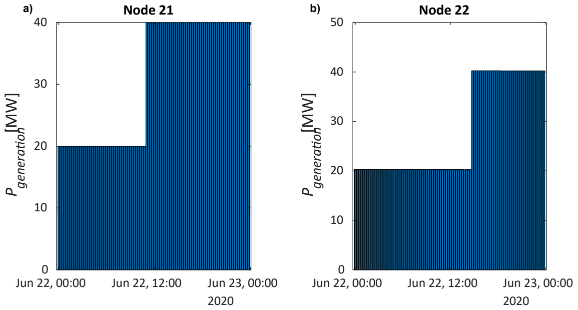

Figure 12: *Change adding production unit to two nodes after OLTC operation*

Figure 13a presents the voltage conditions before and after the operation of the OLTC. The voltage before the activation of the OLTC has already exceeded the permissible limits, and since we turn on the additional generation in nodes 21 and 22 at 00:00, the OLTC level changes at the first moment of the day. This lowers the voltage so that it is within acceptable limits. Then, the OLTC rate remains the same, even though we include an additional 20 MW generating unit in node 21 at 11:00. The OLTC rate increases only when an additional generating unit is connected to the grid at node 22 at 14:45, as shown in Figure 13b.

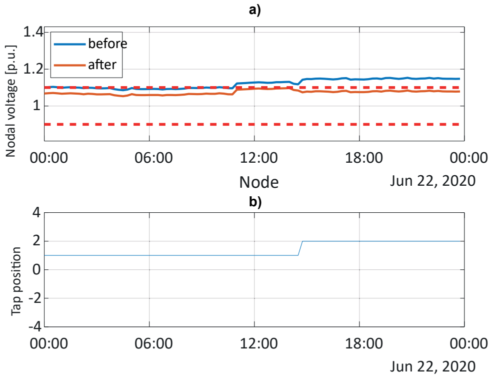

***Figure 13:** Voltage before and after the application of the OLTC and display of the degree of OLTC taps for the selected case over time*

From the latter analysis, it is clear that optimisation algorithms can be used to check the network's limitations, which, however, are not final, but can also be changed by adding dynamic elements such as OLTC.

3.3 Simultaneous addition of load and production units

A particularly interesting analysis is the simultaneous addition of load and production units to different nodes, where one raises and the other lowers the voltage in the node. It is also necessary to realise that there are as many as ninety-six different moments in time available for all 365 days of the year, which, with all the possible combinations of the thirty-five nodes, results in an complex multitude of variants. Figure 14 shows two examples where both combinations on the two selected nodes, 9 and 28, were made, as in the analysis above. In the graph on the left, node 9 is the additional production unit and node 28 is the additional load, while the graph on the right it is the opposite. In the example on the left, calculation started at the previous limits, i.e. in node 9 P_G = +40 MW and P_L = +30 MW, it is noticeable that in the case of the simultaneous addition of both elements, the limit power of both units changes disproportionately, namely the maximum production in node 9 changes to a value of 105 MW and the maximum load in node 28 to 50 MW.

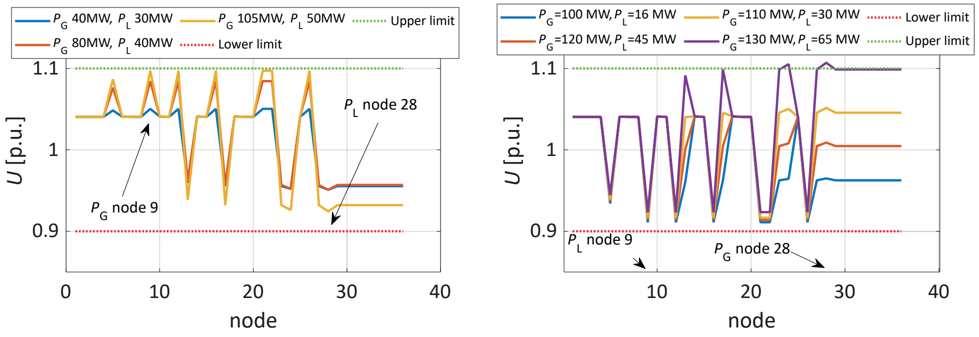

***Figure 14:** Voltage profile in all thirty-five nodes while adding a generation unit into node 28 (left) and adding load (right)*

The graph on the right shows the opposite, as this time node 9 has a load imposed and node 28 a unit of production. The analysis shows that the previous limit values, such as for the case of independent analyses, namely $P_{G\text{-}28node}$ = 100 MW and $P_{L\text{-}9node}$ = 15 MW, do not cause problems. When both values are increased, they tentatively stop at 130 MW for node 28, and 65 MW for node 9.

Such a manual analysis is not suitable, since the changes are contradictory and non-linear, so the use of optimisation algorithms makes sense. In addition, an exact value of the limits is also achieved, which can be changed at will, but in this case they are set to ±10%.

The result of employing the optimisation algorithm to the problems mentioned are displayed in Figure 15. The graph on the left shows the voltage distribution for all nodes where the two target nodes for adding additional units are selected; a production unit is added to node 35, while a load is added to node 25. In the graph on the left, only one in five of the thirty-five optimisation iterations are shown, so that it is easy to see how, when adding the two additional elements, the voltage values increasingly converge towards the limit values. This means that when adding loads, the voltages at certain nodes approach the lower limit of 90% of the nominal value (nodes 8, 11, 15, 19 and 20), and when adding an additional generating unit to node 35, only at this node the voltage rises to the extreme values of 110% of the nominal value. The graph in the upper right shows how the search values change, and the graph below shows the convergence of the optimisation algorithm. It can be seen that the chosen number of iterations is thirty-five, and it proves to be sufficient, as the estimated error is less than 1% and the results are also satisfactory. Depending on the selected location of additional elements in the network, a production unit in node 35, size $P_{G\text{-}35}$ = 28.68 MW, and an additional load in node 25, size $P_{L\text{-}25}$ = 7.17 MW, can be connected to the network for the selected day and time.

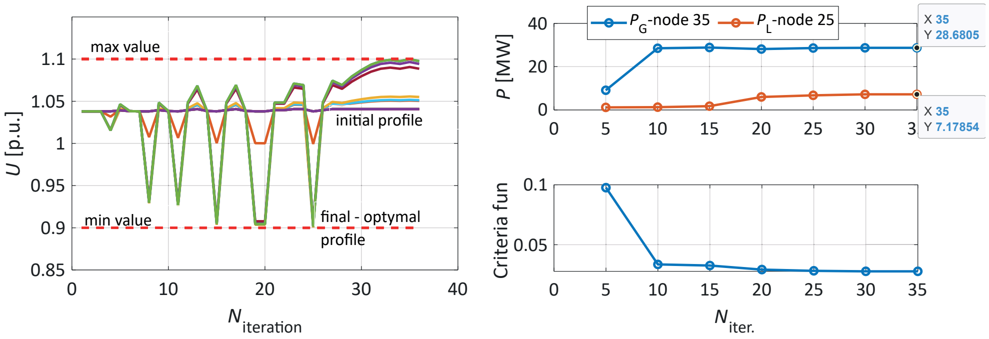

Figure 15: *Voltage profile in all thirty-five nodes while adding a generation unit into node 35 (left) and adding load to node 25, optimisation evolution on the right*

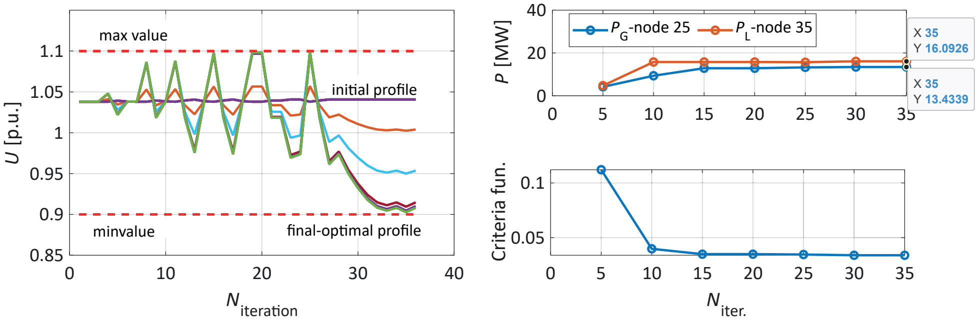

Figure 16: *Voltage profile in all thirty-five nodes while adding a generation unit into node 28 (left) and adding load (right)*

Due to the large number of possible combinations, only one further example is presented, where the two mentioned nodes switched types; so now there is additional load at node 25 and additional production at node 35. The result of the analysis is presented in Figure 16, where the change in the voltage distribution in twenty-five iterations can be seen on the left. This time, some nodes in front of the load node increase in voltage (compared to the results in Figure 14), and similarly, the voltage decreases in the last node where we add production, which is the opposite of the case in Figure 14. In the last iteration, when a satisfactory convergence has already been achieved, we can evaluate both values and conclude that in this case an additional production unit, size $P_{G\text{-}25}$ = 13.43 MW, can be added to node 25, and an additional load to node 35, namely $P_{L\text{-}35}$ = 16.09 MW

4 CONCLUSIONS

An inaccurate and inconsistent assessment regarding the possibility of connecting new elements in the distribution network can have a discriminatory effect on an individual, as their request to connect a new device may be rejected or permitted to a lesser extent than desired. This article presents an integrated approach to network analysis, which is carried out on a real example and verified with real measurements. The treated network already has a few production units as well as larger loads, both of which may increase in the future for objective reasons. The article presents the construction of a model for calculating voltage conditions in the network using standard methods. Verification of the model for any moment in the year is also carried out, so that different scenarios of additional elements in the network can be explored by means of simulation. By random testing and using an unsystematic approach, time-consuming procedures can be replaced by a comprehensive approach, including the use of an optimisation algorithm. The method of differential evolution was used, which finds the maximum value of the search variable for each node at every moment in the year, for either an additional load or an additional unit of production. An upgrade to this is to extend the operation of the network with an OLTC device, which can further improve the voltage profile within the intended limits. Finally, a dual-criteria optimisation is presented, where we simultaneously include both opposing elements in the network, but where, due to nonlinearity and complexity, it is difficult to find the local extrema of the desired function. In the future work, it is possible to upgrade the model to more simultaneous search criteria or to use it as a model example of the entire approach.

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