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Voltage Control in MV Network with Distributed Generation—Possibilities of Real Quality Enhancement

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Abstract: Connecting an increasing number of distributed sources in MV (medium voltage) and LV (low voltage) distribution networks causes voltage problems resulting mainly from periodic power flows towards the HV/MV (HV—high voltage) transformer station. This temporarily changes the nature of distribution networks from receiving to supply networks and causes an increase in the voltage values deep within the network, often above the permissible level. Therefore, it is necessary to search for new voltage control methods that take into account the active participation of distributed sources. The article proposes a concept of such a system in which the control signals are transformer taps in the HV/LV station and the values of reactive powers generated or consumed by RES (renewable energy sources). These values can be determined either by solving the optimisation problem (according to a given quality indicator criterion) or on the basis of appropriately selected settings of the $Q(U)$ characteristics of the inverters and the HV/LV transformer ratio. The article describes both approaches, pointing to the advantages and disadvantages of each of them.

Keywords: voltage control; voltage quality; renewable energy; metaheuristic optimisation; medium voltage; $Q(U)$ characteristics

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1. Introduction

The article continues and extends the analysis of problems related to voltage control in MV networks, in which a large number of distributed sources have been installed. The variable power generation of these units due to weather conditions causes frequent changes of voltage values. The most severe are voltage increases above 1.1 U_n, which when transformed into the LV level may damage the receivers, or create conditions for switching off the sources (both on the MV and LV side) by overvoltage protections. The volatility of weather phenomena and the randomness operation of protective devices lead to voltage chaos in the network.

In the previously presented work [1], the authors showed that voltage control is possible, in which not only the HV/MV transformer with OLTC (on load tap changer) is actively involved, but also sources connected to the MV grid. These sources, depending on the voltage conditions (related to the variability of the power generation and voltage changes in the HV grid), can control the values of the generated (or consumed) reactive power on the basis of signals sent from the voltage controller.

The concept of voltage control in the MV network proposed in [1] comes down to on-line solving (for every quarter of an hour) of the OPF (optimal power flow) task after prior estimation of the network state and transmission of control variables determined in the computational process to the actuators (tap changer position and source reactive powers). In the considered OPF problem, the objective function is a voltage quality indicator covering all network nodes (the number of nodes is N). The objective function is described by the Equation (1).

The proven effectiveness of the optimisation task solution (the AIG heuristic algorithm [2] was used) is conditioned, however, by high requirements in terms of accessibility to the network model and its ICT equipment. The network model is the result of the process of estimating its state. The use of estimation algorithms at the MV level is not an easy task, although certainly not as complex as in the case of meshed transmission networks. Similarly, solving the OPF task in real time (the research assumed a discrete control for each time window of one quarter of an hour) requires considerable computational expenditure. Thus, the method of optimal voltage control in MV networks presented in [1], hereinafter referred to as the OPFh-MVt method (optimal power flow heuristic—medium voltage for each time period), can be considered attractive and future-proof, but today it is difficult to convince network operators to wider attempts to implement it.

In the present article, the authors set themselves the goal of searching for an alternative method of voltage control in MV networks with distributed generation, the implementation of which would not be as complicated as in the case of the OPFh-MVt method, while the results would be only slightly worse. The novelty of the proposed approach consists in presenting the optimal method of voltage control in the MV network, the results of which are treated as reference. For practical use, a simplified method is recommended, the results of which have also been positively verified. The novelty of the article also lies in the fact that a very large set of data from real objects was used to verify the presented methods.

The article consists of seven sections. The first section contains an introduction to the subject and the purpose of extending research and analyses related to the considered problem. The second section presents a literature review on voltage control in the MV network. The third section contains the formulation of the optimisation task and the description of the algorithm for its solution. The fourth section includes a description of a simplified method of voltage control using the HV/MV transformer tap changer and control of the reactive power of RES sources with given Q(U) characteristics. Section five presents the IEEE 37 test network. The calculation results showing the effectiveness of the proposed control system are included in section six. Section seven provides a discussion of the results and conclusions.

2. Literature Review

The subject of voltage control in MV networks with distributed generation has been the subject of research in many articles. The authors approach this problem in various ways, trying to demonstrate the effectiveness of the proposed methods of solving it. Generally speaking, there are four main groups of methods presented in the works so far:

- Voltage control using only the on-load tap-changer (and/or possibly a capacitor bank);
- Voltage control with the use of on-load tap changer and reactive power generation in RES;
- Voltage control with the use of on-load tap changer, reactive power generation in renewable energy sources and the use of energy storages connected in selected network nodes;
- Voltage control with the use of on-load tap changer, reactive power generation in RES and the use of electrolyser installations connected in generation nodes.

It is also possible to imagine a comprehensive approach to the problem and apply voltage control using an on-load tap changer, reactive power generation in RES, the use of energy stores connected in selected network nodes and electrolyser installations connected in generation nodes.

A number of works have been prepared in which problems resulting from a radical change in the characteristics of distribution networks, previously considered typical (radial system of operation, unidirectional power flow), are considered. Some of them used both classical and heuristic optimisation methods. The selected voltage control evaluation criteria identified by the authors in other articles are presented below:

- Minimisation of the cost of power and energy losses [3],
- Minimisation of power losses [4,5],
- Minimisation of energy losses [3],
- Minimisation of costs related to active power losses and reactive power flow [6],

- Minimisation of the voltage quality index (while in the literature there are indicators expressed with the use of various dependencies) [7–11],
- Minimisation of the number of tap changer position changes [9].

The above-mentioned selected criteria, ways of solving the outlined problems and many other similar issues can be found, for example, in works [12–24].

The easiest way to adjust is to use only the on-load tap-changer. For example, in [25] the authors used the multi-agent system to find the optimal values of the transformer tap changer in order to minimise the objective function, which is the positive three-phase voltage deviation. This function represents the sum of voltage deviations in the observed nodes.

In article [26], the authors present the results of analyses for the IEEE 13 test network at various load levels. Changing the transformer taps is controlled by the line drop compensator, depending on the required voltage level in the selected network node.

An interesting approach can be found in article [9], where the objective function is the difference between the transformer's taps at two consecutive time points (assuming that there is one transformer in the network). The optimisation task is to minimise the number of tap changer position changes during the day while meeting the constraints.

Study [10] uses a method consisting in adaptive adaptation of the transformer's tap changer to the assumed voltage value in a fictitious node. The electrical distance of this node from the MV busbars in the 110/MV station is also appropriately determined so that the expected voltage value in it influences the quality indicator of the voltage quality in the entire network.

In article [8], seven different objective functions related to the optimal voltage control in the MV and LV distribution networks are considered. HV/MV transformer ratios and MV/LV transformers ratios are addressed as decision variables.

In addition to the transformer tap changer, the ability to generate reactive power in RES is also used for voltage control. A number of works on this subject have been written. An example may be article [6] where the decision variables are the reactive powers of the micro-sources in the LV network at the given transformer ratio. The objective function is the sum of costs related to active power losses and costs related to the reactive power flow. The internal point method is used to solve the optimisation problem.

Decision variables in the form of reactive power generated or consumed by RES are also used in work [27]. The authors consider a three-criteria objective function under the necessary constraints. Weights for individual criteria are determined dynamically.

In [28], a two-criteria objective function is considered, consisting of the sum of the costs of power losses and the costs of switching operations as well as voltage deviations. The objective function contains two criteria, therefore weighting factors were used. The weighting factors are selected by the analytic hierarchy process (AHP), described in article [29].

In [30], a single-criterion objective function is used in the form of a voltage quality indicator. The optimisation task was to minimise the objective function by changing the HV/LV transformer ratio and the reactive power of the sources, but only in a few operating states. The applied method of linear optimisation was locally convergent.

The use of reactive power generation or consumption in RES was also analysed in works [31–36].

The next group of papers are articles devoted to the use of electricity storage to optimise the operation of the distribution network [37–45]. The authors of these studies apply various criteria and methods for solving voltage problems.

In the work [37], the authors consider the medium voltage network and the water supply network, which is a controlled energy storage. Water consumption control (grid load control) is used to control the voltage by changing the electricity consumption. The article [38] presents the Predictive Control (MPC) Model, which consists in the optimal coordination of generation in renewable energy sources, energy storage and the operation of the on-load tap changer. One of the most interesting functions of the objective is included in [39]. The objective function has two normalised criteria (with values ranging from 0 to 1). Each of the two considered criteria is taken into account with an appropriate weighting factor. The first criterion is the voltage deviation, while the second criterion is the total capacity of the energy storage.

In the work [40], in order to solve the voltage problems caused by a large number of photovoltaic installations, a coordinated method of controlling distributed energy storage systems in combination with traditional control (OLTC) has been proposed. A novel charging and discharging system for battery energy storage systems (BESS), which uses real network data, is described in [41]. The article [42] proposes to create an optimal battery charging/discharging schedule in the context of power loss minimisation. Determining the capacity of battery energy storages installed in a grid saturated with photovoltaic installations, in order to control their operation, was proposed in [43]. A review of energy storage technologies and systems and the methods of their application, for example in power grids, have been presented in the works [44,45].

Some authors use the available measurements and also look for the relationship between the voltage values and the power generated in the sources to implement the voltage control process in the distribution network. Some of these methods do not require knowledge of the network model, due to the application of neural solution (deep learning) and artificial intelligence. Such attempts can be found, for example, in works [46–51].

The use of voltage value measurements to control the operation of the distribution network without the knowledge of the network topology is presented, for example, in [46]. In the work [47], the authors replace with a linear model the non-linear dependencies between the voltage values in the distribution network nodes and the generated power. Optimal voltage control in a distribution network containing renewable energy sources, which does not require knowledge of its model, was considered in the works [48,49]. In the article [50] a data-driven-based optimisation method for var-voltage sequential control was proposed. An interesting algorithm of voltage control in the distribution network is presented in [51]. The authors also emphasise that the proposed method requires the exchange of information only between neighbouring photovoltaic installations, which significantly reduces the communication complexity.

The applied deep learning algorithms can be combined with optimisation tasks. Examples of such research and analyses are presented, for example, in the works [52–55].

The P2G (power to gas) technology has also been developed for some time, and alkaline water electrolysers (AEL)—[56,57], used for the production of "green hydrogen", are considered the cheapest and the most accessible. From the point of view of voltage control they are controlled active power loads connected at the generation nodes. Within a few years there has been a significant increase in interest in this method of storing surplus electricity from renewable sources [56–64]. Some works concern the optimal size and layout of electrolyser installations. Part of the articles concern the elimination of negative voltage effects in networks saturated with RES installations. The analyses are conducted for both the medium voltage and low voltage distribution networks.

As shown in the literature review, there are many ways to assess the quality of voltage and the effectiveness of its control in power grids. Some of them use a complicated mathematical framework, in others the objective function of the control process is difficult to understand intuitively by a combination of technical and economic indicators. In some solutions it is not necessary to know the network model, but it is necessary to transmit signals from all its nodes and sources. According to the authors of the presented article, only simple voltage quality assessment criteria have a chance for practical use by network operators and sensitive consumers. Therefore, the search for complex alternative criteria was abandoned, assuming that simple criteria such as (1) having a simple physical interpretation (analysis of the deviation from the criterion value) can be treated as the appropriate objective function of a more or less complex optimisation processes.

Comparing the works of other authors with the analyses performed in this article, its originality should be emphasised, consisting in the application of an innovative approach to the problem of voltage control in the considered MV network. It consists in:

- Using the actual annual power generation characteristics by the solar and wind sources under consideration ($P_{gi}(t)$);
- Using the real characteristics of the power received at nodes ($P_{\mathrm{L}i}(t)$) of the considered network;
- Using the real waveform of voltage changes in the 110 kV network ($U_{\mathrm{HV}}(t)$);
- Determination of the optimal values of the control variables with the use of the proprietary OPFh-MVt algorithm for all the considered grid states and determination of global control assessment indicators;
- Formulation of a simplified method of voltage control using the interaction of the OLTC system and active operation of the source control and its evaluation in relation to the reference results obtained with the OPFh-MVt method.

3. The Method of Voltage Control in the MV Network Using the Results of Cyclic Solving of the OPF Task

The method proposed in this paper is implemented on the basis of the solution of the optimisation task.

The considered objective function was described by the following equation:

$$F(\mathbf{x}, \mathbf{y}, \mathbf{z}) = \sqrt{\sum_{i=1}^{N} \left(\frac{U_i - U_\mathrm{o}}{U_\mathrm{n}} \right)^2} = \mathrm{Ind}\, U, \quad (1)$$

while the individual variables of the control process are defined as follows:

$\mathbf{x} = [\vartheta,\ Q_{\mathrm{G}1} \ldots Q_{\mathrm{G}k} \ldots Q_{\mathrm{G}p}]$—vector of control variables formed by transformer ratio (ϑ—discrete variable) and reactive power of p sources connected to the MV network;

$\mathbf{y} = [U_{\mathrm{HV}},\ P_{\mathrm{L}1} \ldots P_{\mathrm{L}m}, Q_{\mathrm{L}1} \ldots Q_{\mathrm{L}m},\ P_{\mathrm{G}1} \ldots P_{\mathrm{G}p}]$—vector of independent variables, formed by: HV network supply voltage, active and reactive power received in m nodes and power generated in p sources, not subject to change during optimisation calculations,

$\mathbf{z} = [U_1 \ldots\ U_j,\ \delta_1 \ldots \delta_j]$—the vector of state variables containing nodal voltages and their arguments (total number of network nodes $j = p + m$).

The results obtained by that method can be treated as reference for the other simplified solutions. A diagram of the control process is shown in Figure 1.

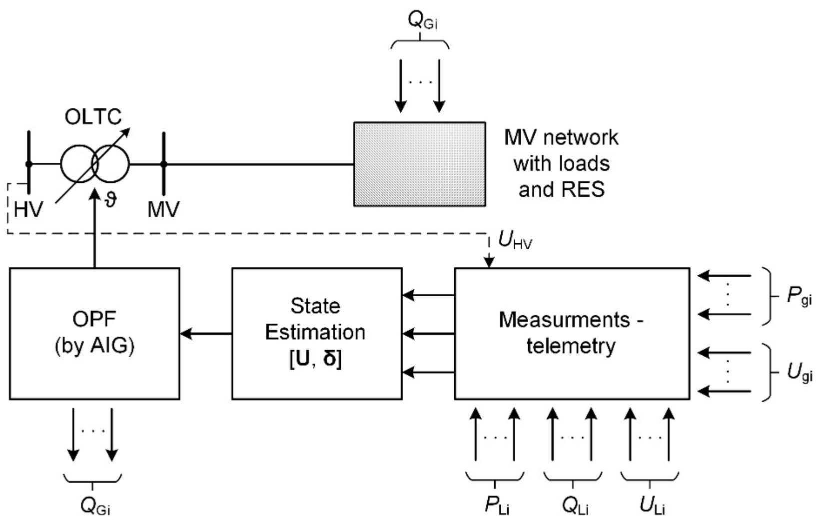


Figure 1. Diagram of the OPFh-MVt voltage control method, control signals—transformer ratio ϑ and reactive power of RES systems.

For the solution of the optimisation task, the original proprietary heuristic algorithm called AIG (Algorithm of Innovative Gunner) was used, described in detail in [2] and successfully tested to solve many technical and mathematical problems—[2,65]. The AIG algorithm is characterised by the fact that the components of the decision vector are subject to "multiplicative" modifications in subsequent iterations, described by the relationship

$$x_l^{(k+1)} = x_l^{(k)} \cdot g_l(\xi) \tag{2}$$

in contrast to "additive" modifications, used in other metaheuristic methods [65–73], described by the relationship

$$x_l^{(k+1)} = x_l^{(k)} + \Delta x_l^{(k)} \tag{3}$$

where k is the next iteration, functions $g_l(\xi)$ and $\Delta x_l^{(k)}$ are a symbolic notation and a characteristic of the heuristic method used.

The innovativeness of the AIG algorithm results from a new method of determining the value of decision variables in subsequent iterations. This means that in each step of the iteration process, the previously obtained solution is corrected by appropriately selected multipliers. This is a fundamental difference compared to other metaheuristic algorithms, in which the process of creating a new solution is based on adding an appropriate component (appropriate for a given method) to the previous solution or searching in its environment. The authors of the article, as the authors of the AIG algorithm, find more and more applications in which its speed and accuracy of calculations are used. It is also used in other applications, even very distant from the power industry [74–77].

In the case of the AIG algorithm, the $g_l(\xi)$ functions have the form of the cosα function and its inverse $(\cos\alpha)^{-1}$, while α and β are correction angles drawn from the variable interval $(-\alpha_{\max}, \alpha_{\max})$ and $(-\beta_{\max}, \beta_{\max})$ by means of the uniform distribution. A block diagram showing the operation of the AIG algorithm is shown in Figure 2 [2].

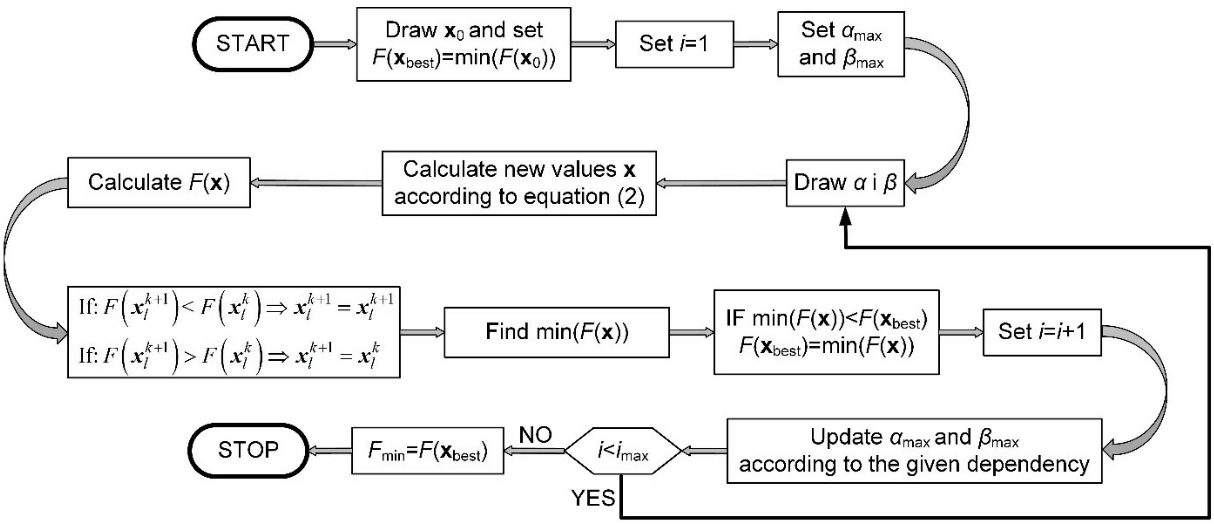


Figure 2. Block diagram of the AIG algorithm (k is the iteration number).

The objective function $F(\mathbf{x})$, which is minimised, is described by Equation (1). The following limitations are checked during the optimisation process:

- Minimum and maximum transformer ratio values (ϑ). The calculations were based on a 10 MVA transformer with 19 operating positions of the tap changer, within the range of ±9 (plus the tap in the zero position);
- Minimum and maximum reactive power values for each renewable energy source (Q_{Gmax}, Q_{Gmin}). It was assumed that each RES has the ability to generate/consume a maximum reactive power equal to ... P_{nG}; since the maximum power of each power plant is 1 MW, the possible reactive power control is within ±0.4 Mvar;
- Minimum and maximum voltage values for all network nodes (U_i); the voltage was kept in the range from 0.9 U_{nMV} to 1.1 U_{nMV};

- Permissible values of current carrying capacity of sections of power lines ($I_{l\max}$). The following value was assumed in the calculations:
    - $I_{l\max} = 355$ A for conductors with a cross-section of 120 mm^2,
    - $I_{l\max} = 290$ A for conductors with a cross-section of 70 mm^2,
    - $I_{l\max} = 170$ A for conductors with a cross-section of 50 mm^2,
    - $I_{l\max} = 145$ A for conductors with a cross-section of 35 mm^2,

and the permissible power value o of the transformer (S_{nT}). The calculations assume the rated power of the transformer $S_{\text{nT}} = 10$ MVA.

The calculations were performed in Matlab and PowerWorld Simulator, version 22. The main script was written in Matlab, while the power flow calculations were performed in PowerWorld. The connection between the two programs is possible owing to the SimAuto plug-in (included with PowerWorld), which also acts as an interchangeable computing engine that enables data exchange between different applications. The computation process starts with running the script in the Matlab environment. Then, during each iteration, remote connection with the PowerWorld floodlight program is performed, the parameters of the power system elements are changed, and the calculation results are downloaded [1,65,78]. The flow chart of the optimisation process is presented in the general diagram (Figure 3).

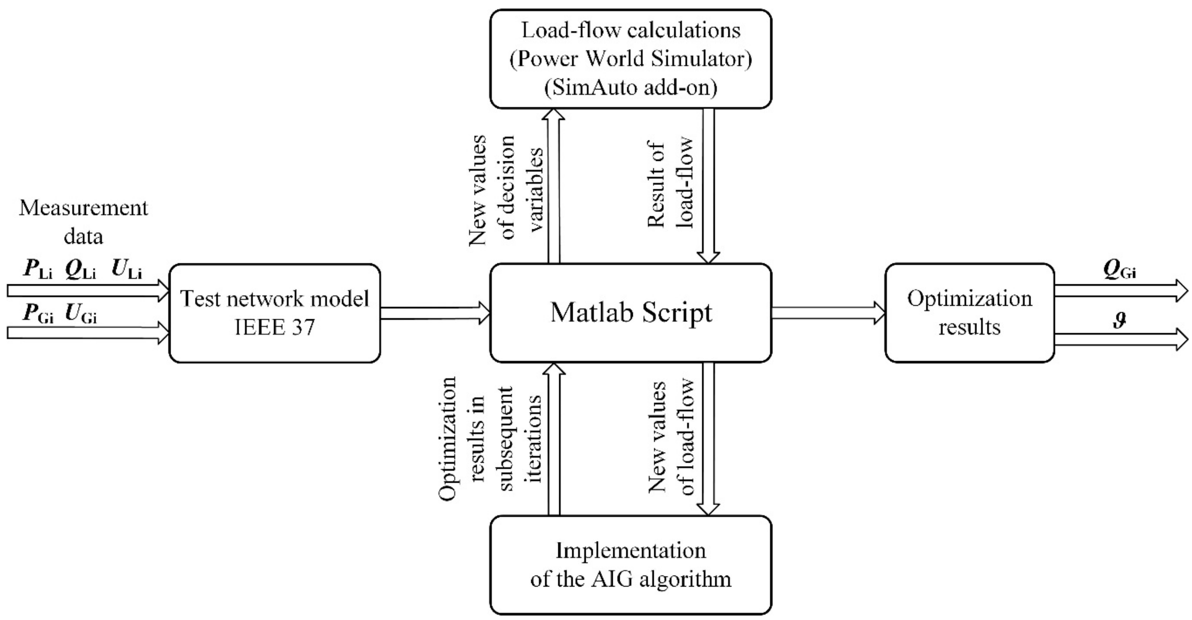


Figure 3. General scheme of the organisation of the computational process used in solving the optimisation task.

Changing the input parameters or downloading the calculation results is done with the use of appropriate commands, appropriate for a given programming environment. After the AIG algorithm is run, optimisation calculations follow, and the results are saved in a file.

4. A Simplified Method of Voltage Control in the MV Network with the Use of the Tap Changer of the HV/MV Transformer and the Active Influence of Distributed Sources

The basic voltage control system in the MV network is shown in Figure 4a. Very often, the role of this system is limited to keeping a constant, set voltage value on the lower side of the HV/MV transformer. The OLTC switches the transformer taps on the HV side, in the considered case their number (up and down) was ±9, and the voltage change per tap $\Delta U_{\text{T}} = 1.11\%$. These are typical values. At the same time, in many cases, the neutrality of RES in terms of generation (or consumption) of reactive power is sought by setting their power factors to the value cos $\varphi = 1$. Admittedly, this method of voltage control ensures its set value near the transformer busbars (most often it is 1.05 U_n), but it does not allow for controlling the increase in voltage deep inside the network, which was shown for the test cases. Such a method of control should be assessed negatively.

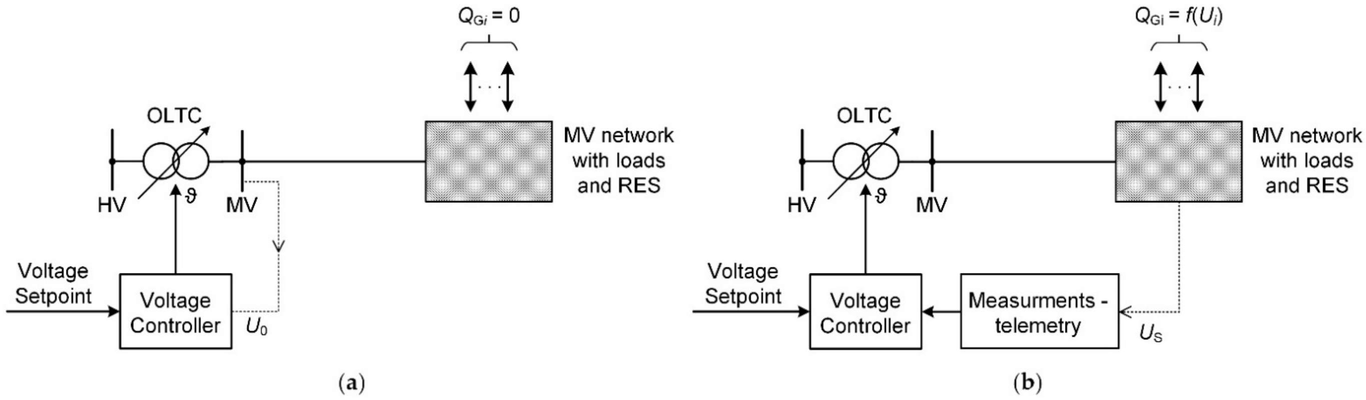


Figure 4. Simplified methods of voltage control in the MV grid with distributed generation: (**a**) traditional regulation—keeping a constant voltage value on the MV busbars, (**b**) keeping a constant voltage value in an optimally selected node deep inside the grid and activating the characteristics of *Q(U)* inverters.

In order to take advantage of the regulation possibilities of the sources, it is possible to consider the way of operating with a defined level of reactive power generation. As the problem is too high voltage values caused by the power flow towards the MV busbars, the method of operation involving reactive power consumption depending on the value of the generated active power, i.e., $Q_G = -0.4\ P_G$, was also considered. This method of voltage control should also be assessed negatively, because in some cases the voltage value is underestimated, and unnecessary reactive power flows increase losses.

The improvement of voltage conditions in the MV network can be achieved also by keeping a constant voltage value not on the transformer busbars, but inside the network—Figure 4b (node *s*). Depending on the possibility of signal transmission from the network to the controller and the method of selecting the set point, the effects of such control may be varied, but they have a significant impact on reducing the negative influence of RES on voltage conditions and improve the efficiency of the OLTC system.

The activation of the characteristics of the *Q(U)* inverters results in a further improvement of voltage conditions in the vicinity of installation of RES units. The required shape of the *Q(U)* characteristic is given in standards [79–81]. Its individual characteristic points can be individually set for each source. Analyses taking into account the characteristics of reactive power as a function of voltage in a network node can be found, inter alia, in the works [7,32,65,82–85]. Figure 5 shows the characteristic that seems to be the most appropriate for a network with a large number of RES—when the voltage reaches the value of 1.1 U_n, the source absorbs the maximum possible value of reactive power.

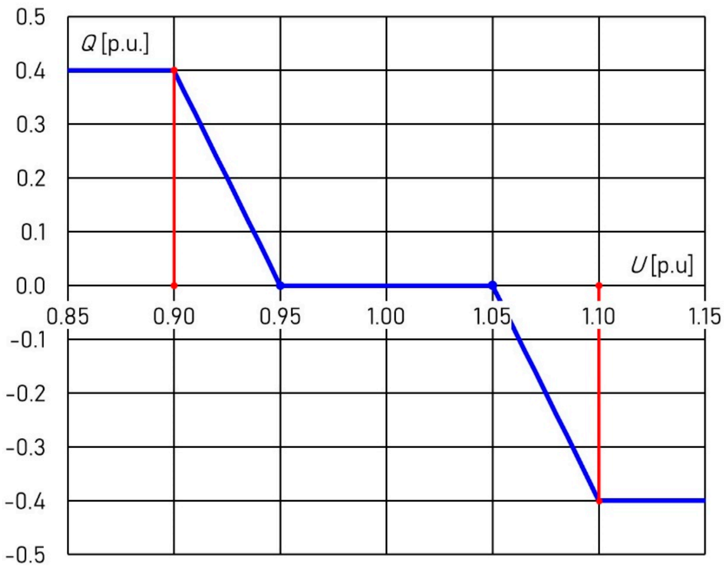


Figure 5. The $Q(U)$ characteristic of the inverter of the RES installation (photovoltaic and wind farm) selected for the analysis of the effectiveness of the voltage regulation in the MV grid.

5. Test Network

The subject of the research was the IEEE 37 network [86], which was assigned a voltage of 15 kV (MV). The supply station has a 10 MVA transformer with a ratio of ϑ = 115/16.5 kV/kV ± 9%. The operation of five sources was considered in this network—three photovoltaic farms and two wind turbines with the same rated power of 1 MW. The diagram of the IEEE 37 network and the location of the sources are shown in Figure 6. A detailed description of the network structure as well as the resistance and reactance of individual branches modelling the lines are presented in Table 1. Table 1 also contains cross-sections and lengths of individual line sections, which show that the network in question is typical for rural areas with an average level of electrification. The network load includes MV/LV transformer substations connected in all nodes (the total number of nodes is m = 37, MV/LV substations are not marked in the Figure 6). Table 1 presents the data of the individual sections of the MV line. Table 1 presents the data of the individual sections of the MV line.

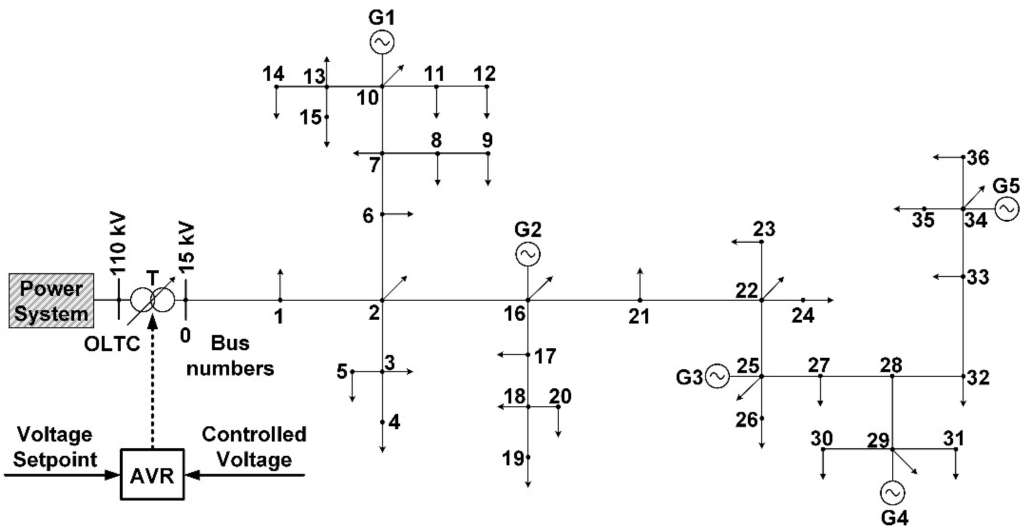


Figure 6. IEEE 37 test network diagram [86].

Table 1. Parameters of the individual sections of the MV line.

Power Line from-to	Line Length l, km	Conductor Cross-Section S, mm^2	Resistance R, Ω	Reactance X, Ω
0–1	1.80	120	0.43	0.18
1–2	1.80	120	0.43	0.18
2–3	0.50	70	0.20	0.20
2–6	0.50	70	0.20	0.20
2–16	2.50	120	0.60	0.25
3–4	0.70	70	0.29	0.28
3–5	0.60	70	0.25	0.24
6–7	1.20	70	0.50	0.48
7–8	1.20	35	0.99	0.48
7–10	2.00	70	0.82	0.80
8–9	0.70	35	0.57	0.28
10–11	0.50	35	0.41	0.20
10–13	1.20	35	0.98	0.48
11–12	1.20	35	0.98	0.48
13–14	0.50	35	0.41	0.20
13–15	0.90	35	0.74	0.36
16–17	1.50	35	1.22	0.60
16–21	2.90	120	0.69	0.29
17–18	0.90	35	0.74	0.36
18–19	0.50	35	0.41	0.20
18–20	0.70	35	0.57	0.28
21–22	2.50	120	0.60	0.25
22–23	1.00	35	0.82	0.40
22–24	1.00	35	0.82	0.40
22–25	1.80	35	1.47	0.72
25–26	0.50	35	0.41	0.20
25–27	2.00	35	1.63	0.80
27–28	1.50	35	1.22	0.60
28–29	0.90	35	0.74	0.36
28–32	1.80	35	1.47	0.72
29–30	1.00	35	0.82	0.40
29–31	0.60	35	0.49	0.24
32–33	1.50	35	1.22	0.60
33–34	1.90	35	1.55	0.76
34–35	0.80	35	0.65	0.32
34–36	0.80	35	0.65	0.32

The authors had hourly measurements of the load and generated power in the MV network and the voltage on the 110 kV (HV) side registered for the entire year, which gives 8760 h. The record of changes in these values is shown in Figure 7. Power generation in wind turbines (Figure 7c) and in photovoltaic farms (Figure 7d) corresponds to real changes resulting from weather conditions (wind speed, solar radiation intensity, cloud cover).

Figure 8 shows the results of the voltage analysis carried out for the tested MV network in the conditions of complete no RES generation. The voltage values determined for 8760 cases form a characteristic multicoloured "band" which, with increasing distance from the MV busbars of the HV/MV transformer, slightly widens and falls downwards. In all cases and for each node, the voltage must be between 1.01 and 1.05 of the rated voltage. Thus, the voltage quality in the state of no generation, even without introducing numerical indicators, can be assessed as good.

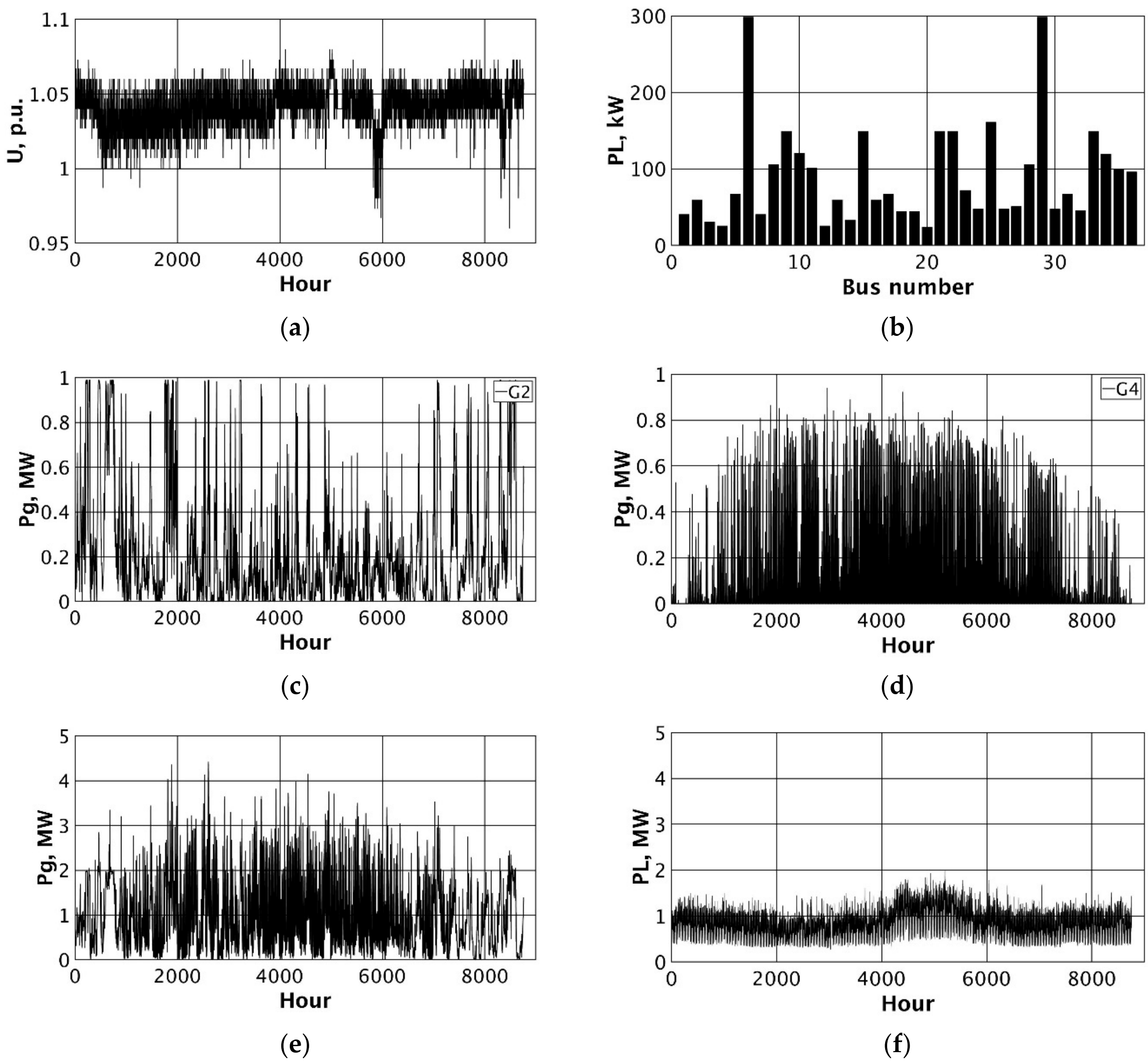


Figure 7. Drawn variable values for subsequent calculation cases (**a**) HV values, (**b**) maximum loads of individual nodes, (**c**) power generated in wind turbine (G2), (**d**) power generated in photovoltaic farm (G4), (**e**) total power generated in renewable energy sources, (**f**) total load power in MV nodes.

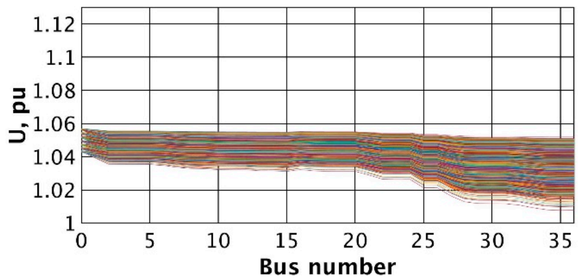


Figure 8. The results of the voltage analysis in the IEEE 37 network without the participation of sources.

6. Calculation Results

Below, the results of the analysis of voltage values in the MV nodes, carried out over a period of one year with the use of the three control methods discussed above, are presented and compared.

6.1. Assessment of Voltage Quality Using a Traditional Circuit

Figure 9 shows the results of the analysis carried out with the assumption that the control system keeps the value of 1.05 U_n on the transformer LV bus (node 0 of IEEE 37 network) by influencing the OLTC. Generators operate with coefficient cos φ = 1 or absorb reactive power according to defined relation $Q_G = -0.4\ P_G$. As can be seen in Figure 9a,b, the band of voltages clearly widens, exceeding in many cases the critical value of 1.05 U_n. As the voltage drops below 1.02 U_n, under no-generation conditions, it is impossible to ensure stable voltage conditions on the lower side of the MV/LV transformers of the consumers connected at nodes 25 to 37. The values of the voltage quality index, defined by Equation (1), many times exceed the value of 0.1 defined as acceptable (Figure 9c,d). High generation with reactive power absorption slightly reduces the maximum voltage values, but for small generation cases the voltage value drops below the value equal to 1.

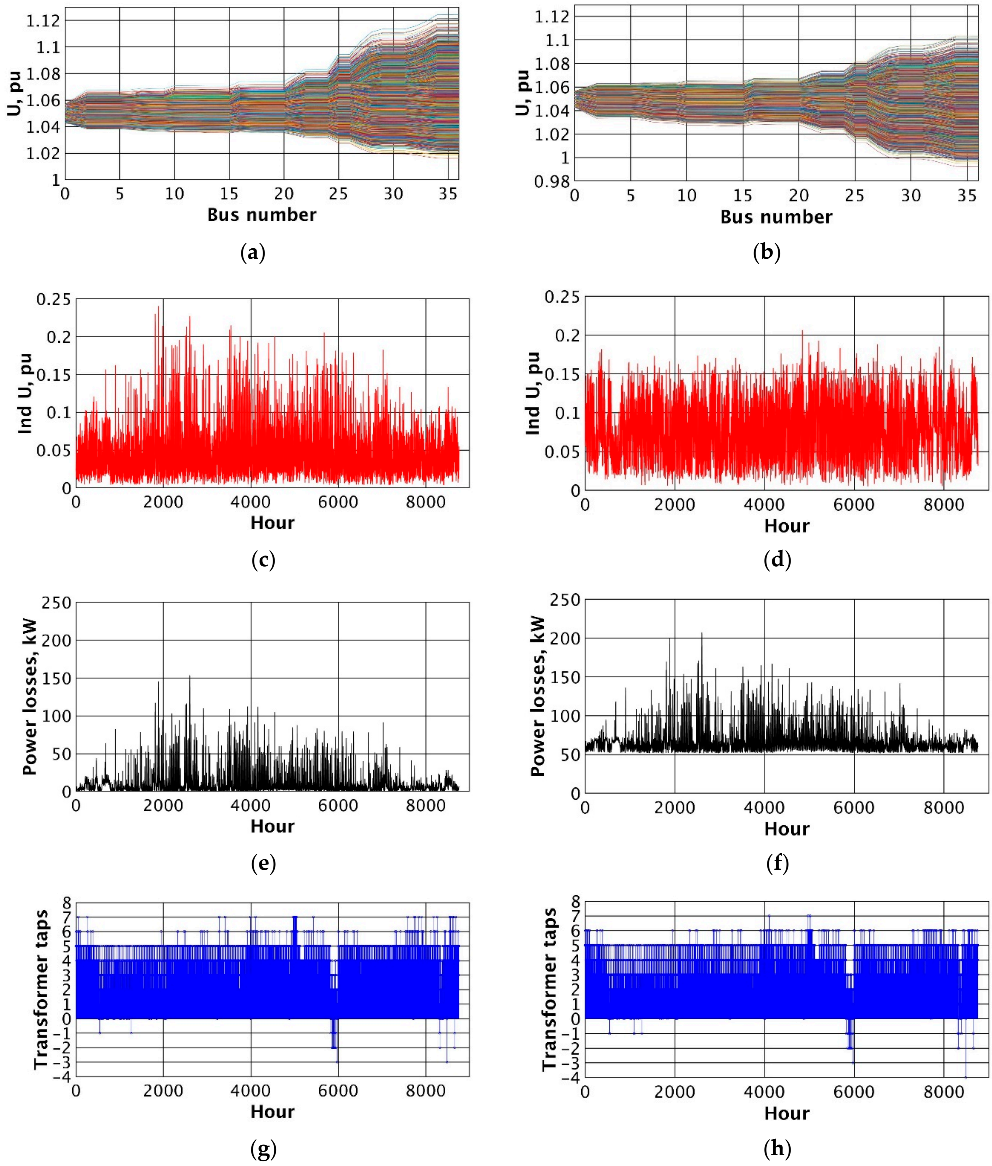


Figure 9. Annual effects of voltage control using the traditional method for two cases of reactive power generation in sources: cos φ = 1, $Q_G = -0.4\ P_G$ (**a**) voltages in network nodes, cos φ = 1; (**b**) voltages in network nodes, $Q_G = -0.4\ P_G$; (**c**) voltage quality indicator, cos φ = 1; (**d**) voltage quality indicator, $Q_G = -0.4\ P_G$; (**e**) power losses, cos φ = 1; (**f**) power losses, $Q_G = -0.4\ P_G$; (**g**) OLTC position, cos φ = 1; (**h**) OLTC position, $Q_G = -0.4\ P_G$.

6.2. Voltage Quality Assessment Using the OPFh-MVt Method

Figure 10 shows the results of the analysis carried out with the assumption that the control system operates in accordance with the principles of the OPFh-MVt method. As a result of the optimisation process, repeated in each time window on the basis of data from telemetry and grid state estimation, the HV/MV transformer ratio values and the reactive powers of the sources connected to the grid are determined. As can be seen in Figure 10a, the band of voltages becomes significantly narrower and even at the end of the network it ranges from 1.04 U_n to 1.08 U_n. Moreover, the voltage quality indicator (optimisation task of objective function) decreases in value and in the worst case it practically does not exceed the level of 0.1.

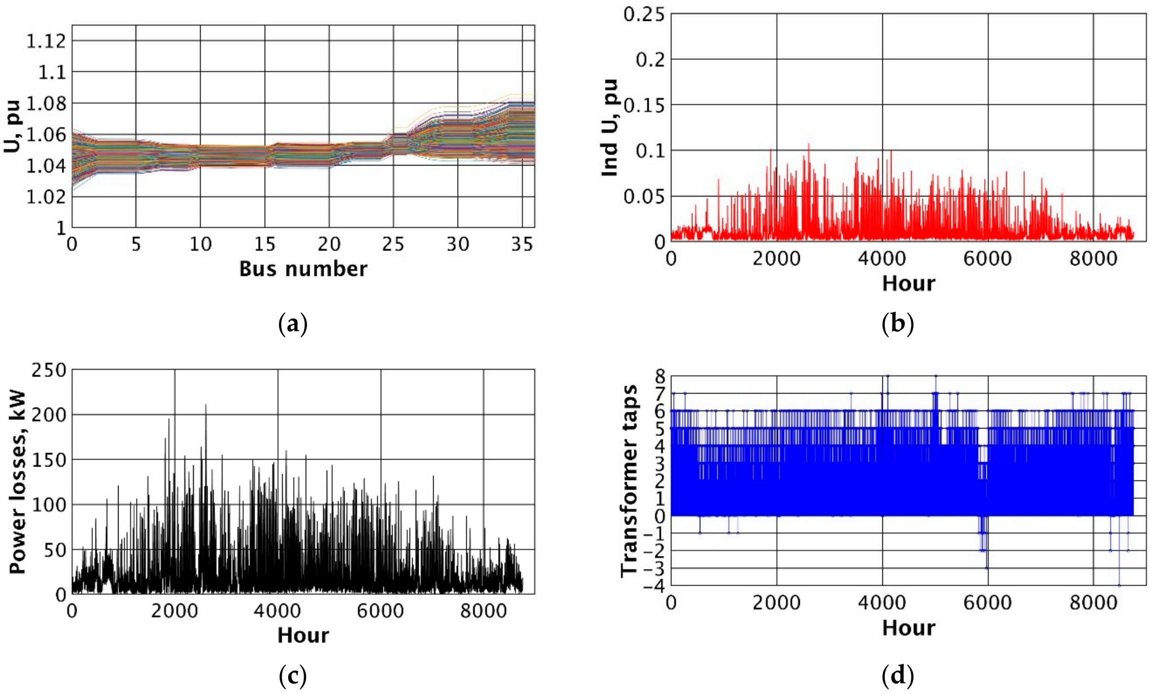


Figure 10. Results of the analysis of the effects of voltage regulation using the OPFh-MVt method: (**a**) voltage values in the network nodes for all hours of the year, (**b**) annual changes in the voltage quality index, (**c**) annual changes in power losses in the network, (**d**) annual changes in the position OLTC.

Generators produce or absorb reactive power so as to minimise the value of the indicator. Changes in the value and direction of reactive power flows take place very rapidly, as they are forced by the course of the optimisation process (Figure 11). The result of high reactive power flows is a significant increase in power losses, which is visible in Figure 10c (compared to Figure 9c). The transformer ratio values changed with OLTC, on the one hand, limit the voltage at the end of the network, but on the other hand, they allow to keep the appropriate voltage value near the station busbar.

Referring to the course of the optimisation process, it should be stated that the AIG algorithm ensures its high convergence and accuracy. Figure 12 shows changes in the best values of the objective function for the selected case.

Figure 12 shows how quickly the AIG algorithm finds the optimal solution. Additionally, for comparison and verification, Figure 12 shows the course of the optimisation process according to the known heuristic algorithms—cuckoo search (CS) and moth-flame optimisation (MFO) compared to the proprietary AIG algorithm. The chart shows that practically 100 iterations are enough to find the optimal solution, so the optimisation process runs efficiently. For AIG, it is even more convergent than for the other tested algorithms.

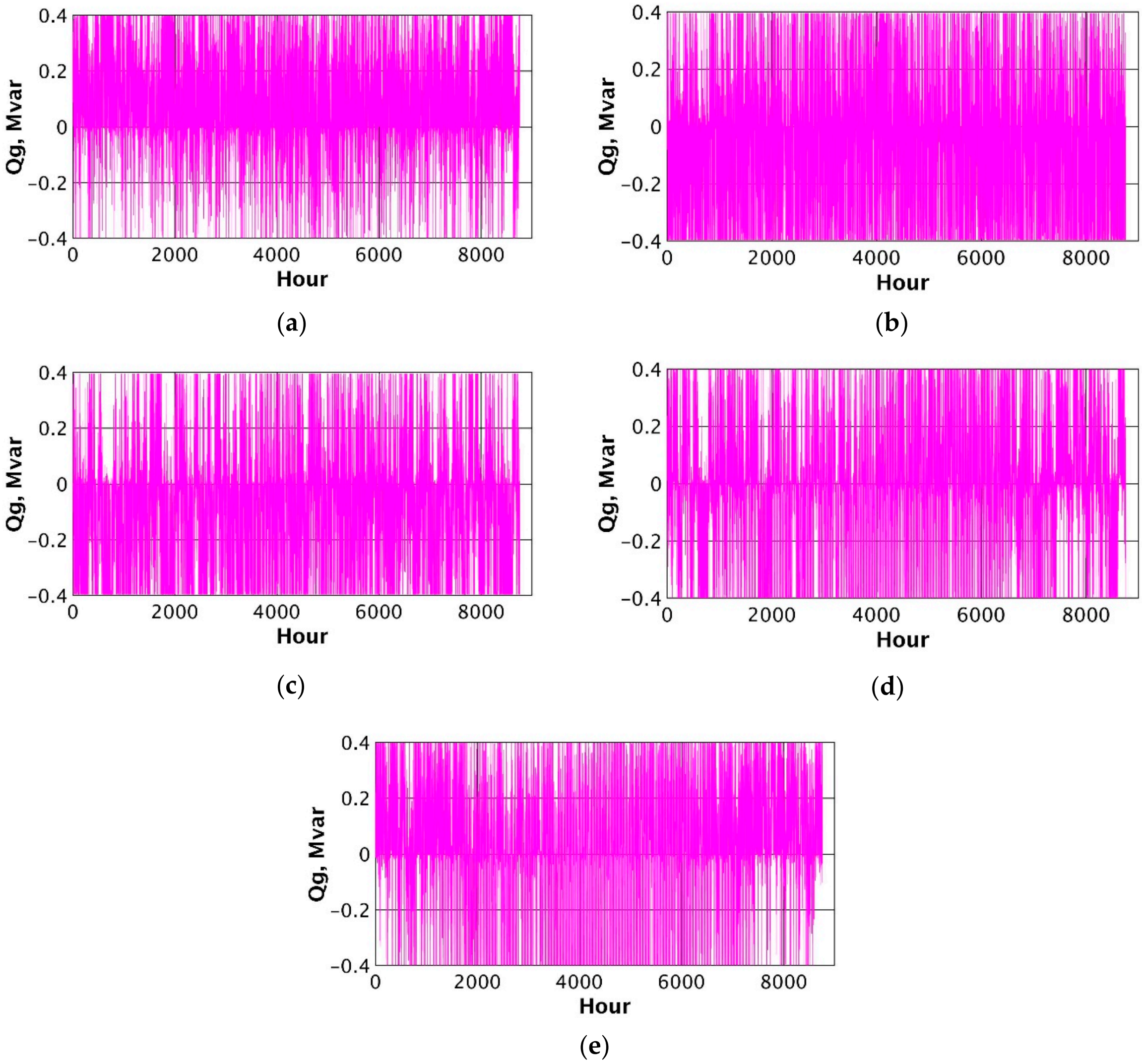


Figure 11. Changes in reactive power generation and consumption of individual RES in the voltage regulation process according to the OPFh-MVt method (**a**) G1, (**b**) G2, (**c**) G3, (**d**) G4, (**e**) G5.

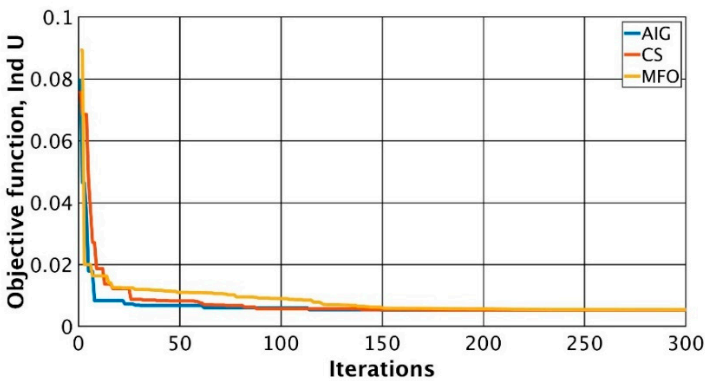
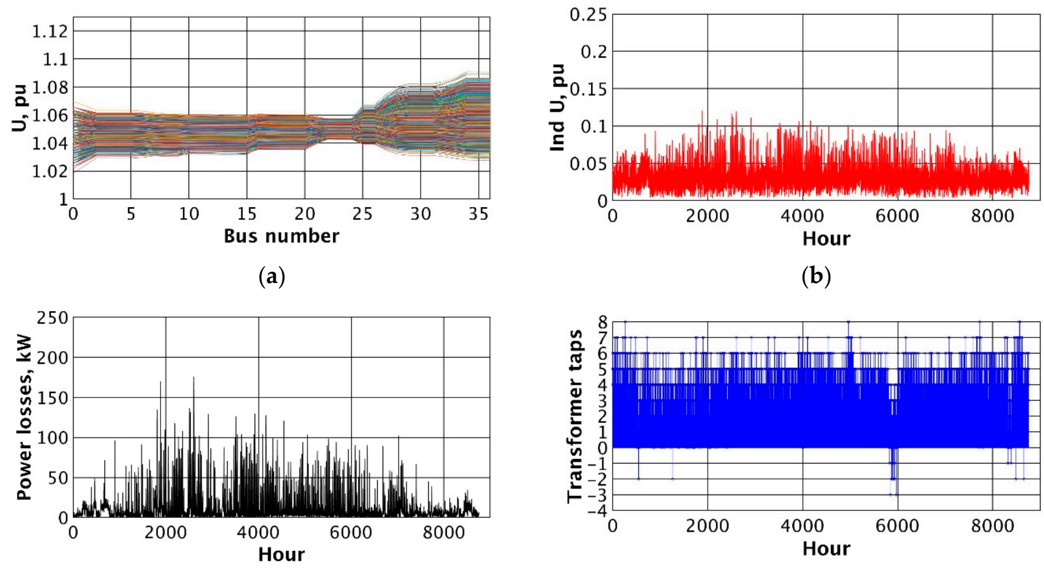


Figure 12. Changes of the best values of the objective function in subsequent iterations for AIG, CS and MFO algorithms.

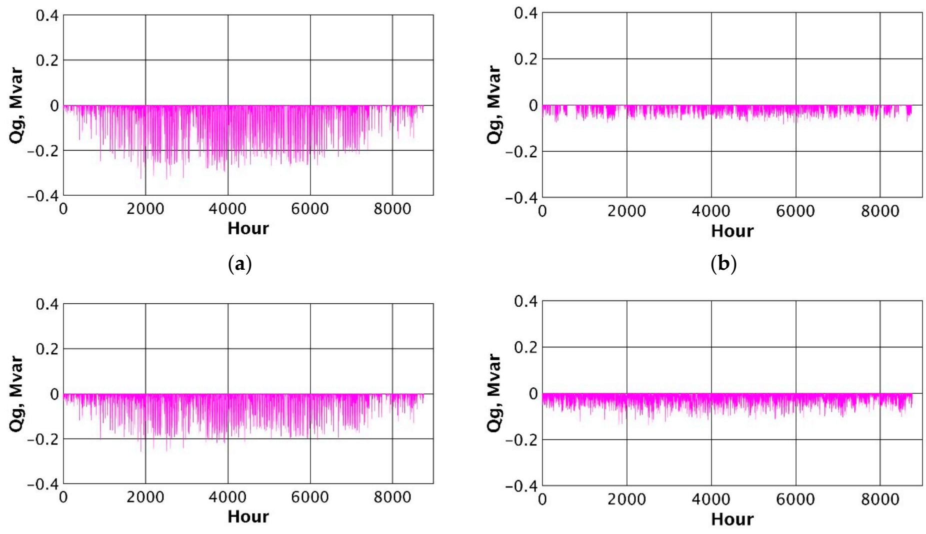
6.3. Description of the Method Using OLTC Control Related to the Voltage inside the Network with the Simultaneous Use of the Q(U) Characteristics of Individual Sources

Figure 13 presents the results of the analysis carried out with reference to the alternative, simplified method of voltage control, described in point 4. The value of the transformer ratio is determined by the controller to which the voltage is applied from the deep inside of the network. The selection of the node for which the regulator tries to keep the value of 1.05 U_{n} (internal reference node) is the result of the offline optimisation process, described in the next section. Additionally, for each source, $Q(U)$ characteristics are activated, which ensure local voltage limitation under high-generation conditions. The band of voltages visible in Figure 13a is slightly less coherent than for full optimisation (Figure 10a), but much more favourable than for conditions with traditional control method (Figure 9a,b). The power losses in Figure 13c are clearly smaller than in the case of control OPFh-MVt (Figure 10c). It is a natural consequence of limiting the generation of reactive power in sources only to ensure the appropriate local voltage value, without striving to minimise the global value of the quality indicator Ind U. This is shown in Figure 14—the values of the reactive power absorbed are significantly lower than in the case of the OPFh-MVt control. It can be seen that they do not reach their maximum values and the generation of reactive power does not occur at all.



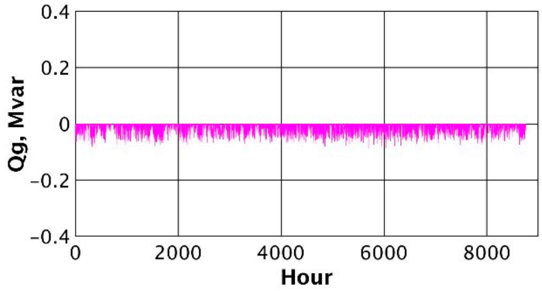
(a) (b) (c) (d)

Figure 13. Graphs for data after optimisation (**a**) voltage values at all MV network nodes, (**b**) voltage indicator, (**c**) power losses, (**d**) transformer tap.



(a) (b) (c) (d)

Figure 14. *Cont.*



(e)

Figure 14. Changes in reactive power generation and absorption of individual RES in the voltage control process according to the simplified method—OLTC + $Q(U)$ (**a**) G1, (**b**) G2, (**c**) G3, (**d**) G4, (**e**) G5.

6.4. Selection of the Internal Reference Node

The concept of selecting the control reference node not on the HV/MV transformer busbars but inside the network has been known for years. Such a node was called the "centre of gravity of the network load" and it was modelled (without real voltage transmission) by means of a elements (R, X) inside the controller. This solution was called current compensation. With the development of distributed generation, this concept should be modified. As shown in Figure 4b, the reference node for control with OLTC should be appropriately selected, located inside the network and transmission of the voltage value to the controller should be provided. The question is how to select a reference node? The general rule for such a choice can be described as "deep but not too deep". For each of the 8760 h of the year, the effectiveness of the method described in Section 6.3 was simulated, with each of the 37 test network nodes selected as the reference node (in total, calculations were made for 8760 × 37 = 324,120 cases). The following figures show the results of these simulations.

Figure 15 shows the values of the Ind U indicator for the entire IEEE 37 network determined for the simulations described above. A characteristic band of numerical values is visible and despite such a large number of results, it can be clearly seen that the lowest values of the voltage quality index were achieved when node 22 was selected as the reference node. Interestingly, this choice is appropriate for different load conditions, different values of generated power, and different voltage values in the 110 kV network. Placing the reference node too close to the generation sources (deeper into the network, e.g., nodes 28,33,36) results in a significant reduction in the voltage value on the HV/MV transformer busbars and deterioration of the voltage quality for the nodes closer to the transformer and consequently for the entire network. Hence, the rationale for the principle is as defined above (deep but not too deep).

Figure 16 shows the results of three of the 8760 simulations selected for the high generation distributed source state, the medium generation level and for zero generation and high load. The results of the calculations confirm the correctness of choosing node 22 as the reference node. Similar values result from the analysis of the value of the Ind U indicator averaged for the whole year, presented in Figure 17. The choice of node 22 as the reference node minimises the value of this indicator, which confirms the correctness of the selection.

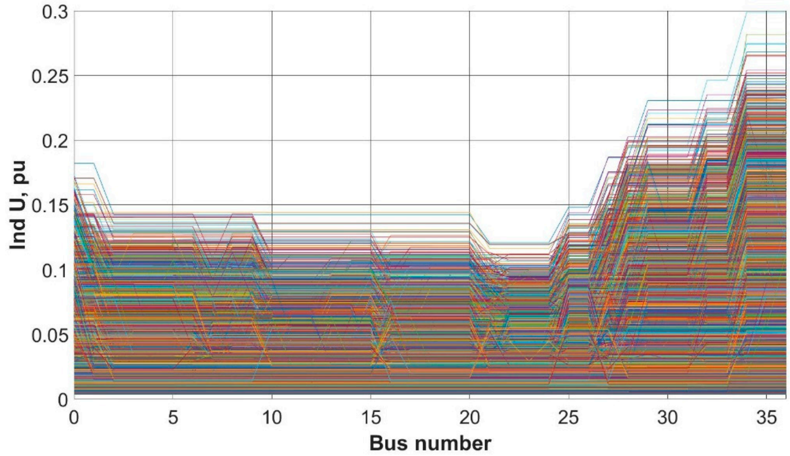


Figure 15. The results of the simulation assessment of the voltage quality indicator Ind U for the IEEE 37 network depending on the selection of the reference node, the voltage of which is maintained at a given level by the OLTC controller.

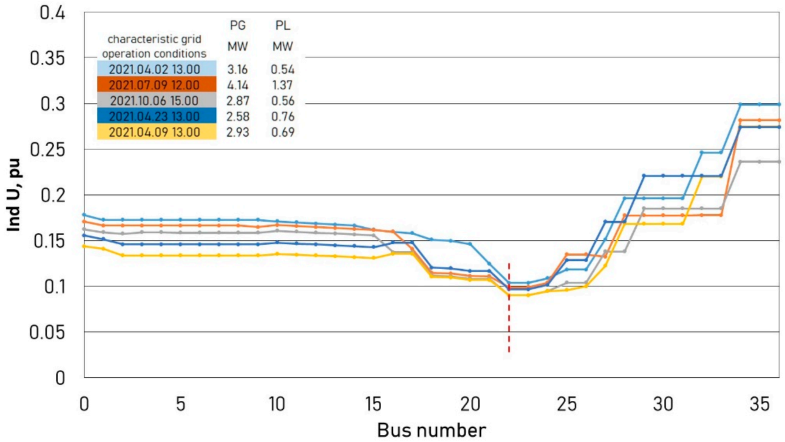


Figure 16. The results of simulations determining the voltage quality index for five characteristic grid operation conditions depending on the selection of the reference node.

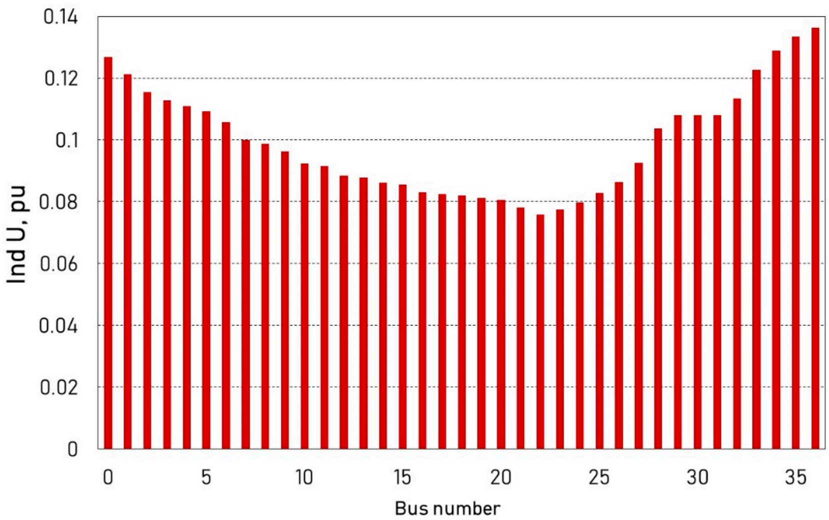


Figure 17. Simulation results determining the voltage quality index averaged for the entire year depending on the selection of the internal reference node.

6.5. Discussion and Comparison of Results for the Analysed Voltage Control Methods

Table 2 summarises and compares the statistical assessment of annual changes in the voltage quality index and relative power losses for the considered cases of voltage control in the considered IEEE 37 network. The rows of the table marked with a superscript [1] refer to network operation without RES generation. The introduction of RES generation with no changes in the voltage control method (transformer with OLTC, zero reactive power—table rows marked with index [2] increases the average value of the voltage quality index from 0.034 to 0.048, while its maximum value increases more than three times (from 0.076 to 0.24). This is a significant deterioration of the voltage quality, with a noticeable increase in relative power losses (on average from 0.740% to 1.208%, maximum from 1.73% to 26.7%, with high generation and very low load).

Table 2. Annual changes in the voltage quality and power loss index.

	$\overline{W}$	σ	Max	Min	Med
Ind U [1]	0.034	0.011	0.076	0.011	0.033
Ind U [2]	0.048	0.035	0.240	0.003	0.038
Ind U [3]	0.011	0.014	0.108	0.001	0.006
Ind U [4]	0.033	0.018	0.121	0.004	0.029
$\Delta P/P_0$ [1] [%]	0.740	0.260	1.730	0.238	0.724
$\Delta P/P_0$ [2] [%]	1.208	2.040	26.70	0.050	0.441
$\Delta P/P_0$ [3] [%]	2.760	3.590	38.30	0.040	1.327
$\Delta P/P_0$ [4] [%]	1.355	2.350	30.57	0.051	0.466

[1] Network with traditional control, the transformer with OLTC keeps the voltage value equal to 1.05 U_n on the MV (bus number 0) buses; no active power generation. [2] Network with traditional control, the transformer with OLTC as describe above, RES variable generation of active power, zero value of reactive power of RES. [3] Voltage control in the MV network using the results of cyclic solving the OPF task. [4] A simplified method of voltage control in the MV network with the use of the tap changer of the HV/MV transformer, keeping the voltage value equal to 1.05 U_n in the depths of the network (bus number 22) and the local influence of reactive power of distributed sources.

The use of voltage control as a solution to the OPF task and the impact on both the transformer ratio (OLTC) and the reactive power of generating sources (RES) significantly improve its quality—Table 2, values with the upper index [3]. The average value of the indicator Ind U decreases four times to the value of 0.011, which is significantly better than in the absence of any generation. Unfortunately, the intensive use of reactive power generation (or absorption) by RES systems leads to a noticeable increase in power losses. Their average relative value increases more than twice (to 2.76%). Thus, to the technical and computational problems related to voltage control based on OPF, there is a doubt related to the clear relationship between the improvement of voltage quality and an increase in power losses.

As stated earlier, a method ensuring relatively easy implementation and a positive impact on voltage quality with a simultaneous limited increase in losses is the use of appropriately selected *Q(U)* characteristics, while striving to keep a constant voltage level in the depths of the network (in Table 2, the rows with the superscript [4]. The voltage quality index is practically the same as for the state with zero generation (0.033), the power losses increase, but to the value of 1.355%, i.e., they are twice lower than in the case of the OPF solution. Thus, the presented results confirm the thesis about the possibility of selecting a relatively easy method of improving voltage conditions in a network with a large number of RES systems.

7. Conclusions

Numerous connections of distributed generation sources to the MV grid cause unfavourable voltage effects, characterised in high-generation conditions by an increase in the voltage values inside the grid, above the permissible level. As the analyses presented in the article showed, the traditional method of regulation with OLTC and keeping a constant voltage value on the MV busbars of the HV/MV transformer does not prevent this phenomenon and it is necessary to look for new solutions.

Undoubtedly, the development of telemetry and software for estimating the state of the MV network allows for the optimisation of its operating conditions, including the optimisation of the voltage control system. The control variables are defined as the result of the optimisation problem—the use of the original AIG heuristic algorithm is shown. Simultaneous control of the HV/MV transformer ratio and influencing the generation or absorption of reactive power by RES units dramatically improves the voltage conditions in the MV network, even with a very high share of distributed generation. Unfortunately, this solution is associated with a significant increase in power losses.

Technical difficulties related to the implementation of such an advanced method may be replaced by a compromise by the operation of OLTC on the basis of a measurement signal from the inside of the network and the effect of the activation of the *Q(U)* characteristics of distributed sources. The results of the analyses obtained on the basis of the actual annual HV voltage waveforms and power generated by wind turbines and PV systems indicate that such control can now be treated as a standard for MV grid operation. However, it is justified to continue working on the implementation of more advanced voltage control methods, such as OPFh-MVt described in the article.

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