http://doi.org/10.35784/iapgos.1928

A REVIEW OF VOLTAGE CONTROL STRATEGIES FOR LOW-VOLTAGE NETWORKS WITH HIGH PENETRATION OF DISTRIBUTED GENERATION

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Abstract. *Deterioration of voltage conditions is one of the frequent consequences of connecting an increasing number of photovoltaic sources to the low-voltage (LV) power grid. Under adverse conditions, i.e. low energy consumption and high insolation, microgeneration can cause voltage surges that violate acceptable limits. Research shows that the increase in voltage is the main limitation for connecting new energy microsources to the LV network and forces the reconstruction of the network. An alternative to costly modernizations can be the implementation of appropriate strategies for controlling network operation to maintain the voltage at the required level. The article presents an overview of the methods and concepts of voltage control in a low-voltage network developed so far to mitigate the undesirable phenomenon of voltage boosting. The focus was mainly on local methods—not requiring communication infrastructure—as best suited to the conditions of Polish distribution networks. Gathering the results of many tests and simulations carried out in different conditions and on different models allowed for the formulation of general conclusions and can be a starting point for further research on a control method that can be widely used in the national power system.*

Keywords: voltage control, distributed power generation, photovoltaic systems, power distribution lines

PRZEGLĄD METOD REGULACJI NAPIĘCIA W SIECIACH ELEKTROENERGETYCZNYCH NISKIEGO NAPIĘCIA Z DUŻYM UDZIAŁEM GENERACJI ROZPROSZONEJ

Streszczenie. *Jedną z częstych konsekwencji przyłączania do sieci elektroenergetycznej niskiego napięcia (nn) coraz większej liczby źródeł fotowoltaicznych jest pogorszenie warunków napięciowych. W niesprzyjających warunkach – przy niskim poborze energii i wysokim nasłonecznieniu – mikrogeneracja może powodować podskoki napięcia przekraczające dopuszczalne granice. Badania pokazują, że wzrost napięcia stanowi podstawowe ograniczenie dla przyłączania nowych mikroźródeł energii do sieci nn i wymusza przebudowę sieci. Alternatywą dla kosztownych modernizacji może być wdrożenie odpowiednich strategii sterowania pracą sieci pozwalających utrzymać napięcie na wymaganym poziomie. W artykule zaprezentowano przegląd opracowanych dotychczas metod i koncepcji regulacji napięcia w sieci nn mających na celu opanowanie niepożądanego zjawiska podbicia napięcia. Skupiono się głównie na metodach lokalnych – nie wymagających do prawidłowego działania infrastruktury komunikacyjnej – jako najlepiej przystosowanych do warunków polskich sieci dystrybucyjnych. Zebranie wyników badań i symulacji, przeprowadzonych przy różnych założeniach i na różnych modelach, pozwoliło na sformułowanie ogólnych wniosków i może stanowić punkt wyjścia do dalszych badań nad metodą sterowania mogącą znaleźć szerokie zastosowanie w krajowym systemie elektroenergetycznym.*

Słowa kluczowe: sterowanie napięciem, rozproszona generacja, systemy fotowoltaiczne, elektroenergetyczne sieci niskiego napięcia

Introduction

The need to reduce carbon dioxide emission on a global scale has led to the emergence of international agreements forcing changes on many levels in the economy and industry around the world. These changes have greatly affected the power generation sector. The demand for zero-emission energy sources has resulted in dynamic development of renewable sources. In addition to building high-capacity power plants, investments have also been made in microinstallations connected to the low-voltage network which are primarily intended to meet the energy needs of individual households, and secondly, to supply the excess power to the utility grid. Photovoltaic (PV) sources constitute the overwhelming majority of household prosumer sources in Poland. Although the share of photovoltaic microinstallations in the total installed capacity is still small (about 350 MW in February 2019, i.e. 0.8% of the installed capacity [51]), this share is growing faster every year. Therefore, one should be prepared for the consequences resulting from the high penetration of distributed sources in the LV network.

The paper is structured as follows: section 1 briefly discusses the negative impact of distributed sources on a low-voltage network, focusing on the phenomenon of voltage rises. Section 2 presents various classifications of voltage control methods in a network with a high share of PV sources. Sections 3 and 4 describe an overview of local, centralized and decentralized control methods. Section 5 provides a comparison of control methods.

1. Impact of DERs on low-voltage network

The appearance of distributed energy resources (DERs) in a low-voltage network changes the way it operates. With a high concentration of photovoltaics, bidirectional power flows may occur in the network, previously only occurring at higher voltage levels. One of the consequences of this is a voltage rise at the end of the lines. On the one hand, this phenomenon can improve the quality of the power, reducing voltage drops, but on the other hand, under unfavorable conditions, it can cause the upper allowable voltage limit to be exceeded. This phenomenon, called "overvoltage" or "voltage boosting", limits the PV hosting capacity of the grid [32]. However, in many cases, voltage boosts only occur for a relatively short period of the year, which makes costly modernization of the lines and transformers economically unreasonable. A more cost-effective means is to implement a control strategy to maintain the voltage within desired limits.

2. Classifications of voltage control methods

The paper presents an overview of voltage control strategies based on research carried out in low-voltage distribution networks with a large share of photovoltaic systems in Germany, Belgium, Italy, Denmark, Great Britain, the USA and others. The methods were classified according to the division adopted by the International Energy Agency: into local, centralized and decentralized methods [4, 39]. Strategies such as energy storage, demand side management (DMS) and cooperation strategies between photovoltaic sources and electric vehicles can also be considered as measures to counteract voltage problems. However, they are a separate group of methods and have not been included in the review.

Local voltage control strategies do not require any type of communication. The reaction of the PV source results from the settings and internal algorithms of the inverter and the measurement data collected at the point of common coupling (PCC) – voltage, frequency, etc. Based on these, it is possible to change the way the installation operates, e.g. by changing the operating point on the $Q(U)$ curves of the inverter. Also, additional control devices in the network can operate autonomously, based on local measurements. The disadvantage of local methods is the inability to coordinate the entire network. On the other hand, local control is fast and does not require significant initial financial outlays.

Centralized methods allow the coordination of the network thanks to a well-developed communication structure and superior control system. The system requires data from many network nodes (derived from measurements or estimations) and other information such as network topology, and manages grid-connected sources, loads and control devices on their basis. A group of centralized methods ensures the highest level of network optimization, but at the expense of high requirements for the level of automation of components and expansion of communication infrastructure.

Decentralized voltage control strategies combine the features of local and centralized methods. The essence of decentralized control is independent control and coordination of system subsets, but without control from the system operator center.

Other divisions are also used, but they all relate to the range and methods of communication used in the control strategies. In [53, 60], a division into methods of coordinated (centralized), semi-coordinated and decentralized (distributed) control was applied. In [16], the methods are divided into five groups: voltage control in PV inverters, decentralized control, coordinated control, methods using STATCOM compensators and methods based on demand response strategies. In [41], voltage control methods are divided into centralized, decentralized autonomous and decentralized coordinated methods. In [44, 69, 70], a division into centralized, decentralized and distributed methods is introduced. In [22], the authors grouped the methods into decentralized autonomous control, decentralized peer-to-peer coordination, hierarchical control and centralized control.

Note the naming differences, which can be confusing. For example, methods based only on measurements at the point of common coupling may be called local in one paper and distributed in another. Similarly, distributed methods are also often referred to as decentralized methods, using these terms interchangeably. Coordinated methods can also be understood in two ways. The next part of the paper presents an overview of control methods with the division into local, decentralized and centralized methods.

3. Local control strategies

The basic premise of local voltage regulation strategies is autonomy. In the Polish power system, low-voltage networks mostly do not have communication infrastructure. For this reason, local methods may prove to be the best way to increase the network hosting capacity, as they will not burden the system operator with high initial costs associated with the development of the entire network infrastructure.

Local methods include power curtailment, reactive power control in the inverter (cosφ fixed, cosφ (P), Q(U) and combined modes), the use of a transformer with an on-load tap-changer (OLTC), the use of line voltage regulators (LVRs) and static compensators (SVC, STATCOM).

3.1. PV inverter control – generation curtailment

An attempt to use the generated power limitation to reduce the network voltage is described, among others, in [14]. The described method combines the classic MPPT inverter mode (*Maximum Power Point Tracking*) with the Power Curtailment mode and is an alternative to the "on/off" control still used by distribution system operators (DSOs) in some European countries, including Poland. Subsequent research in the field of power curtailment also includes the issue of financial losses incurred by the owner of the installation. The works described in [61, 62] include attempts to evenly distribute costs among all prosumers regardless of the generator's location in the network as well as attempts to determine the maximum allowable generation limitation while ensuring the profitability of PV installations [45]. However, it seems that the use of power curtailment as the only way to increase network hosting capacity is not a sufficient solution in the long run, assuming a further increase in the number of DERs. However, it can be taken into account temporarily when voltage boosts occur sporadically during the year and also as one of the measures (used as a last resort) in combined methods.

3.2. PV inverter control – reactive power control

Among the reactive power control modes in the PV installation inverter, the most basic can be mentioned: Q(U), cosφ(P), cosφ fixed and Q(P) modes.

In [42], based on research carried out in the German distribution network, voltage control methods were compared based on simulations, and laboratory and field tests. The Q(U) and cosφ(P) methods were tested for their effectiveness in increasing the network hosting capacity. Investigating the network in a suburban area clearly indicated the cosφ(P) mode as the more effective method. However, for rural networks, the results for both methods were similar. The effectiveness of limiting voltage boosts for both methods turned out to be high, but the reactive power consumption for the Q(U) mode is significantly lower compared to the cosφ(P) and cosφ fixed methods. For this reason, the report recommends the operation of inverters with Q(U) control. The programmed operating curve should be appropriately parameterized to ensure stability and maintenance of the remaining voltage quality parameters at a sufficiently high level. The issue of the influence of the shape and settings of the inverter operating characteristics on the power quality and stability of the control system is considered in more detail in [3, 13, 54]. In order to optimally select the parameters of the inverter operating curves or to adapt it individually to the location and current network conditions, the literature also suggests the use of optimization algorithms [30, 48, 59].

The conclusions resulting from the U-Control project [42] were confirmed in [57], whose author examined 17 low-voltage networks in Germany in terms of the impact of inverter operating modes—cosφ fixed, cosφ(P), Q(U)—on increasing the network hosting capacity. The method with constant cosφ and cosφ(P) mode proved to have the highest efficiency in the entire study, and the Q(U) mode had the lowest efficiency. Similar results were also obtained in [25, 39]. However, the undesirable reduction of voltage in networks with a predominance of consumed power over generated power, as well as a possible increase in network losses were indicated as the disadvantages of the cosφ fixed and cosφ(P) modes. The advantage of the less effective Q(U) mode is that the voltage conditions at the point of PV connection can be improved if the voltage is too low. Also in [21, 41], based on research in one distribution network in China, it was shown that the operation of the inverter at a constant power factor causes an increase in losses in the network relative to operation at a fixed current or voltage value.

In [26], a new approach to inverter reactive power control is presented. It assumes the installation of an additional device, called a SNOOPI-box (*Smart Network Control with Coordinated PV Infeed*). The basic task of the SNOOPI device is to provide autonomous control of the PV source and inverter by individual parameterization of the Q(U) curve depending on the location of the source in the network. This solution ensures coordinated reactive power generation by all PV sources, thanks to which also sources connected close to the power supply take part in alleviating the phenomenon of overvoltage occurring only deep in the network. This significantly improves the control efficiency, due to the fact that the impact of reactive power on LV voltage is often small. An important advantage of the SNOOPI project is that the devices are autonomous—they do not require communication. Recognition of the connection point to the network is carried out through device algorithms (based on measuring the maximum voltage at the PCC) and does not require any initial configuration or reconfiguration in the event of network expansion.

Another solution, as in [26], ensuring a certain degree of coordination of the entire network, is the parameterization of Q(P) characteristics for each of the PV inverters, as described in [52]. Thanks to the use of voltage sensitivity matrix analyses, it is not necessary to provide communication channels between devices to achieve coordination of PV units. The results show the high efficiency of the control strategy in mitigating voltage rises and minimizing network losses. However, the implementation of the method would be associated with major difficulties due to the necessary change in the parameters of the operating curves each time a new PV unit is connected to the network, which, without remote control of the inverters from the DSO level, seems impossible. According to the authors, this solution could work, however, when the system operator adopts a specific planned level of installed power in PV sources, e.g. in a ten-year perspective, and adjusts the operating curves to the final state. However, this would still result in lower control efficiency during the transition period.

The answer to the problem of the necessary changes in the parameters of the reactive power control curves aimed at increasing the control efficiency may be the method described in [37]. Its main assumption is the ability to autonomously adjust the parameters of the $Q(U)$ curves to the network parameters. This was obtained by measuring the equivalent impedance seen from the generator PCC. Thanks to the known impedance value, it is possible to estimate the impact of the generated power and consumed power on voltage changes at a given point of the network. The impedance also changes with a change in the DER location and changes in network configuration. The study presents sets of parameters for the $Q(U)$ curves that ensure stable and reliable operation of all tested networks. The results of the method are close enough to the results obtained in advanced optimization methods.

3.3. PV inverter control – combined methods

In order to achieve maximum control efficiency, attempts are being made to combine inverter operating modes. In [63, 64], a combined method of controlling the voltage profile of the network is described. It assumes the cooperation of three different methods of controlling the power factor of a distributed source, called: the voltage reference method (*V-Ref*), the reactive power saving method (*Q-Save*) and the reactive power cooperation method (*Q-Coop*). The work continued with the introduction of the duplex method to improve the efficiency by using the inverter power reserve and taking into account the control dynamics [65, 66].

In [33, 34], the effectiveness of voltage limitation methods $P(U)$, $Q(U)$ and the combined method $P(U)+Q(U)$ were compared with the $\cos\varphi = 1$ mode factory set in inverters in the Polish power system. The highest efficiency was obtained for the $P+Q$ combined method. In further studies [48], the authors attempted to optimally select the parameters of the combined $P(U)+Q(U)$ curves using heuristic methods. Optimization of the settings allowed the unused power in PV installations to be minimized. A comparison of the combined methods was also performed in [8], considering the efficiency of $Q(U)$, $\cos\varphi(P)$ modes and combined modes: $Q(U)+P(U)$ and $\cos\varphi(P)+P(U)$. The methods were assessed for their ability to minimize voltage rises, network losses, additional reactive power flows and the necessary reduction of generation from PV sources. The implementation of reactive power control methods allowed the cable line hosting capacity to increase by 26% and the overhead line by 63%. The use of the combined mode allowed an increase of another 25% compared to the previous case. The $Q(U)+P(U)$ mode was indicated as the most effective, and hence recommended, method.

Another local control method combining standard inverter operating modes was proposed in [15]. The described $\cos\varphi(P,U)$ method was compared with the $\cos\varphi=1$, $\cos\varphi=0.9$, $\cos\varphi(P)$ and $Q(U)$ modes. To evaluate the methods, the maximum voltage values occurring in the network were taken into account, but also the transformer load, energy losses and total reactive power consumed by the PV inverters. The $\cos\varphi(P,U)$ method combines the advantages of the $\cos\varphi(P)$ and $Q(U)$ control modes. Network losses measured during the month were significantly lower compared to the $\cos\varphi(P)$ mode. In contrast to the $Q(U)$ mode, lower voltage values were obtained, however, at the cost of a higher load on the transformer.

In the study described in [4, 58], the economic aspect of local control methods was investigated. The costs taken into account include: cost of line modernization, cost of transformer replacement, cost of on-load tap-changer, cost of power losses in the network, costs of reactive power compensation and costs incurred by the owner of the PV unit resulting from the imposed generation limitation. Simulations have shown that the annual costs of network operation are lowest when implementing automatic and continuous reactive and active power control in a $P(U)+Q(U)$ inverter. With a significant increase in the power installed in photovoltaic sources, it is also profitable to install a MV/LV transformer with OLTC. A rigid limitation of the power generated to 70% of the rated power turns out to be a worse strategy. However, assuming that the power will be partly used or stored by the prosumer, it is still a more cost-effective solution than network modernization.

A similar cost analysis was also performed in [9], considering two types of low voltage networks—in suburban and typically rural areas. The costs resulting from the implementation of individual control methods are divided into those charged to the owner of the PV installation (additional losses in the inverter, the need to install an inverter with a higher current efficiency) and incurred by the distribution system operator (additional losses in the lines and transformer). The estimated costs of implementing the considered control methods for both networks are different and depend on the type and configuration of the network. It was noticed that when reactive power control methods were necessary, the total costs charged to all prosumers in the network were much higher than the costs incurred by the system operator.

3.4. Voltage control in the transformer OLTC

Among the methods classified as local due to the lack of remote network monitoring systems, one can also mention the voltage regulation in the VRDT transformer, whose basic implementation is a transformer with an on-load tap-changer (OLTC). In the national power system, transformers with on-load voltage regulation are commonly used at higher voltage levels (HV/MV), however, such a solution is not used in LV networks. The implementation of the voltage level regulation method in OLTC will therefore involve some investment costs on the part of the distribution system operator.

In [49], the effectiveness of the voltage control method in an OLTC transformer receiving information on the voltage level deep in the network based on estimated data was examined. An algorithm for voltage estimation with consideration of generation and load uncertainty using Monte Carlo simulations in time series was presented. This method was compared with the case of full monitoring of distant network points. The results show the high efficiency of the developed method and small differences between actual and estimated voltage values. Its use as the only means of improving voltage levels in the transformer network with OLTC was also proposed in [43]. The study determined the limit of PV connection possibilities for a given network, paying attention to the limitation of OLTC use, resulting from the possibility of undervoltage in lines without connected sources and supplied from the same transformer.

The authors of [68] conducted a study in which the problem of the impact of PV sources on the voltage level and voltage asymmetry in the network was addressed. Single-phase sources were considered as the most problematic and most often installed in LV networks. The goal of the simulation was to choose the optimal distribution of sources into individual phases and to choose a more effective control method – by manually or automatically (depending on sunlight) changing the transformer tap. The best results were obtained with automatic voltage control on the lower voltage side of the transformer and with the most even distribution of sources in individual phases (50%, 25%, 25%). A similar result was also obtained for the distribution of sources determined from the particle swarm optimization (PSO) algorithm. These conclusions were confirmed in [5], in which various scenarios of source distribution in the network, different load and generation levels were considered. The reaction of the network was investigated when controlling the reactive power of the inverter, controlling the voltage in the MV/LV transformer with an on-load tap-changer and using both of these measures simultaneously. It has been shown that the uneven distribution of single-phase sources in individual phases negatively affects the voltage level in the network. The use of the combined method, i.e. cooperation of inverters and automatic voltage regulation in the transformer with OLTC, allows the network connection capacity to be increased the most.

Other studies proposing the use of a transformer with OLTC together with reactive power control in a PV source inverter are described in [24, 29]. In [24], the effectiveness of voltage limitation and thus increased network hosting capacity was confirmed thanks to the use of OLTC and OLTC together with the $Q(U)$ mode. In this study, however, only a uniformly loaded network in each phase and three-phase PV sources were considered. In [29], the effectiveness of various control strategies with OLTC was compared—the use of a classic on-load tap-changer, the use of a single-phase OLTC, reactive power control mode of the inverter and the use of the combined method (single-phase OLTC cooperating with inverters in reactive power control mode). In addition to the voltage level in the network, the effect of microsources on voltage asymmetry, the potential of the neutral wire and losses in the network were also examined. The tested combined method increased the connection capacity of PV sources from 40% to 70% without a significant increase in network losses and potential in the neutral conductor. However, an increase in the voltage asymmetry index was observed.

3.5. The use of line voltage regulators (LVRs)

Another group of voltage regulation methods in LV networks are solutions using line voltage regulators. In [27, 28], an overview of modern devices from the LVR group for low-voltage networks with distributed generation is presented. The operation of LVRs is based on the use of an additional serial transformer in each phase of the line that allows the voltage to be increased or decreased in a continuous or stepwise manner.

In [27, 28], a new solution was proposed based on an LVR which operates with a magnetic-controlled inductor (MCI). Thanks to this, continuous and also stable control was obtained while ensuring uninterrupted operation, even during switching operations in the controller itself. The impact of the regulator's operation on the voltage quality parameters is minimal, which was confirmed in laboratory tests. In the work carried out under the U-Control project [42], the installation of an LVR was also considered as one of the measures to counteract the increase in voltage in the LV network. The focus was on the conditions of cooperation of a classic LVR device, providing voltage regulation in steps, with an MV/LV transformer with OLTC and with the set $Q(U)$ mode in the PV inverters. Research carried out in distribution networks indicates the positive effects of such a solution – the annual reactive energy saving in relation to the $\cos\varphi(P)$ control ranged from 80% to even 98%. At the same time, attention was drawn to the need for proper parameterization of both the LVR and VRDT devices as well as the $Q(U)$ characteristics to ensure the most effective and secure interoperability in the network under normal operating conditions and in the event of failures.

3.6. Use of static compensators

Improvement of the voltage level in the network can also be obtained by using a STATCOM device (Static Compensator) or SVC device (Static Var Compensator) [38]. The use of a STATCOM to improve the voltage conditions in LV networks with a large distributed generation is described in [1, 12, 47, 56]. In [12], research results for Australian networks were presented, in which STATCOM devices were installed to increase the network hosting capacity. The results showed that for a selected network set, the installation of a 10 kvar shunt compensator per phase influences the voltage value within 4–8 V, which is sufficient to keep the voltage within the given limits both at peak demand and at the peak of PV generation. The authors also pay attention to other advantages of the tested STATCOM devices, such as the speed of operation, reduction of voltage asymmetry and shunt connection, which eliminates the need for power interruptions, thus minimizing installation costs. In [1], the impact of the compensator on the network was examined under symmetrical and asymmetrical loads. The obtained results indicate the effective operation of the STATCOM compensator in the field of voltage regulation in the network, elimination of higher harmonics and mitigation of load asymmetry.

4. Centralized and decentralized control strategies

Both centralized and decentralized methods require one-way or two-way communication between devices. The lack of remote monitoring of LV networks in the national power system is therefore the first and most serious obstacle to the implementation of non-local control methods. It cannot be ruled out, however, that in the long-term, there will be solutions enabling both remote measurement of electrical parameters of LV networks, as well as remote control of components of PV installations. However, for strategies to enable full coordination of the network's operation, this solution would have to be implemented on a national scale. It seems that such a scenario, though probable, is still distant.

Centralized strategies include complex network management systems that perform – in addition to voltage control – many other functions, including monitoring of power quality parameters, detection and localization of faults, alarm notification, loss calculation, management optimization and many others. These systems are called DMSs (*distribution management systems*). They enable control of LV networks from the DSO level and coordination of work with MV network management systems. The concepts of the LV network management system are described, among others, in [2, 7, 11, 20, 35, 36, 40].

Decentralized methods use data transmission, but to a limited extent. For this purpose, you can use, for example, PLC communication (*power line communication*) as proposed in [44] and [67]. Both described methods are based on inverter control. This control is carried out in several stages—partly locally and partly in a coordinated manner enabling the even distribution of reactive power consumption to all PV installations operating in the network. PLC communication was chosen because of its low cost and ease of use. Similarly, in [50], communication between neighbouring PV sources was used to evenly distribute the power curtailment into the sources in the network. The decentralized method described in [10] is based on the cooperation of inverters with the controller installed on the MV/LV station. This cooperation serves – apart from lowering the voltage by changing the inverter modes – to reduce the voltage asymmetry in the network. The method described in [69, 70] allows a larger group of PV generators to be controlled in such a way that for each of them, the same ratio of output power (reactive and active power to maximum power) is provided to the network. The division of the network into separate control zones (so-called adaptive zones) is also proposed in [46] and [6]. This division is aimed at simplifying the computational models on which the control system algorithms are based, and limiting the amount of data to be processed and the range of necessary communication. This is achieved by controlling the voltage only in those zones where it is necessary, while the generators in the other zones operate in local mode.

Decentralized methods also include strategies based on the cooperation of additional regulatory devices on the network. [18, 19] describe control of the LV network in a transformer with OLTC. The optimal OLTC tap is determined based on remote voltage measurements in the network. If the tap change proves insufficient, local control of the PV sources is started. In further work [55], the authors carried out field studies of the proposed method using PLC communication. Similarly, in [31], a method of joint control was proposed, through the operation of OLTC and reactive power control in the inverter. In [17], an attempt to combine OLTC work with the operation of distributed static compensators (D-STATCOM) was described. The aim of the work was to achieve better dynamics and continuity of control. STATCOM devices cooperating with PV inverters operating in reactive power control mode were also used in the concept described in [23].

5. Summary

The paper gathers the results of several dozen publications based on simulation and field tests in many countries seeking to increase the power produced in photovoltaic systems by introducing microsources into the low-voltage network. The features of the described voltage control methods are summarized in the table below (Table 1).

The review mainly focused on local strategies not requiring communication. In the coming years, these methods have the greatest chance of being implemented on a large scale in Polish distribution networks. Local strategies will not force a thorough reconstruction of networks in which remote measurements are still not carried out or are carried out only to a limited extent in smart meters. Even if the communication infrastructure for this purpose were created, the law, which does not allow DSOs to remotely access and control prosumer sources, would still be an obstacle. In the longer term, however, it is also worth considering the implementation of decentralized or centralized methods. These methods are also based on local strategies, so research on them will still be useful.

Table 1. Comparison of control strategies

<table>
<tr><th>Methods</th><th colspan="2">Features</th></tr>
<tr><td colspan="3">1. Local control strategies</td></tr>
<tr><td>Generation curtailment (in PV inverter)</td><td>Reduction in the profitability of PV installations;
Low efficiency to increase hosting capacity;
Negative dynamic effects on the network (in the case of step, discontinuous curtailment).
Simplicity of implementation and operation.</td><td rowspan="6">Does not provide network coordination;
Relatively easy to implement;
No communication needed (lower implementation and operating costs, lower failure rate);
High operation speed – low delays in control algorithms.</td></tr>
<tr><td>Reactive power control (in PV inverter)</td><td>Efficiency depends on network reactance;
It may cause additional network losses and additional reactive power flows;
May cause unnecessary voltage drop (cosφ fixed mode);
Requires higher current efficiency of inverters;
Incorrect parameterization may cause instability ($Q(U)$ mode).
Recommended mode: $Q(U)$</td></tr>
<tr><td>Combined methods (in PV inverter)</td><td>Combines the advantages of basic inverter modes;
Requires more complex parameterization of the characteristics.
Recommended mode: $P(U)+Q(U)$</td></tr>
<tr><td>Voltage control in the transformer OLTC</td><td>Additional cost of the device;
Higher transformer failure rate;
Possible undesired voltage reduction to consumers at the beginning of the network;
Control discontinuity (in steps);
Reduced efficiency with network asymmetry (single-phase sources);
Provides high efficiency in combination with another method (e.g. $Q(U)$ mode).
Recommended mode: OLTC+$Q(U)$</td></tr>
<tr><td>Use of line voltage regulators (LVRs)</td><td rowspan="2">High costs of devices;
The need for proper parameterization and optimal selection of network location;
High efficiency, also with asymmetry;
Good operating dynamics.</td></tr>
<tr><td>Use of static compensators</td></tr>
<tr><td colspan="3">2. Decentralized control strategies</td></tr>
<tr><td colspan="3">Require at least basic communication infrastructure (higher cost and failure rate, possible delays in control algorithms).</td></tr>
<tr><td colspan="3">3. Centralized control strategies</td></tr>
<tr><td colspan="3">Require extensive communication infrastructure;
High costs of implementation and operation;
Higher failure rate;
Require a large input set;
High system complexity that may result in delays in control algorithms;
Ensure full coordination of the network thanks to the superior control system.</td></tr>
</table>

The paper includes methods designed for low-voltage networks and tested in such networks. There is more research for medium voltage distribution networks, but these networks have different characteristics, for example due to the higher *X*/*R* ratio, which determines the effectiveness of reactive power control, or the use of transformers with OLTC on a large scale, which are not used in LV networks.

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otrzymano/received: 20.05.2020 *przyjęto do druku/accepted: 15.09.2020*