

I. Trach, M. Belik, O. Rubanenko, V. Miroshnyk, I. Blinov

Simulation of voltage control processes in low-voltage microgrid nodes with renewable energy sources and energy storage system

Introduction. The development of low-voltage microgrids (LV MG) with renewable energy sources requires effective control of their operating parameters, in particular voltage. The **problem** of voltage control in MG is exacerbated by the practical use of remote control systems for grid-forming inverters (GFIs) under conditions of limited data transmission speed. **Goal.** Identification of the features of local voltage control in LV MG nodes connected to distribution systems using reactive power of GFIs, in particular to assess the dependence of the droop-control coefficient on network parameters and to determine quasi-stationary time intervals. **Methodology.** The study was carried out using a newly developed imitation model in the PowerDynamics.jl environment for analyzing the dynamics of LV MGs, which are characterized by predominantly active feeder resistance and take into account the specific operating features of GFIs. **Results.** It has been established that the operating modes of LV MG connected to the distribution system can be considered quasi-stationary over intervals longer than 60 s, which allows the use of static control characteristics without taking into account fast transient processes. The operation of the model was analyzed under conditions of reactive power reduction at the MG input using a PI controller and maintaining a specified value of GFI reactive power. **Scientific novelty.** A new computational model has been developed which, unlike existing ones, enables comparison of different methods of reactive power distributing among a group of distributed energy sources and investigation of the features of voltage regulation using GFIs. **Practical value.** Using the developed model, an analysis was performed and the dependence of the voltage droop-control coefficient on the GFI reactive power was determined. Quasi-stationary intervals for power and voltage in LV MGs were established. The developed model confirms the effectiveness of voltage control through GFI reactive power in different MG operating modes. Practical recommendations for setting GFI parameters and information transfer speed in LV MG control systems were formed. References 56, tables 2, figures 7. **Key words:** microgrid, quasi-stationary state intervals, grid-forming inverter, PV-generation, reactive power.

Вступ. Розвиток мікромереж низької напруги (ММ НН) з відновлювальними джерелами енергії потребує забезпечення ефективного регулювання параметрів їх режимів, зокрема напруги. **Проблема** регулювання напруги в ММ НН підсилюється використанням на практиці систем віддаленого управління інверторами, що формують мережу (GFI), в умовах обмеженої швидкості передавання даних. **Мета.** Визначення особливостей локального регулювання напруги у вузлах ММ НН, приєднаних до систем розподілу, з використанням реактивної потужності GFI, зокрема оцінювання залежності коефіцієнта droop-control від параметрів мережі та визначення часових інтервалів квазі-стаціонарності. **Методологія.** Дослідження виконано з використанням нової розробленої розрахункової моделі у середовищі PowerDynamics.jl для аналізу динаміки ММ НН, яка має переважно активний характер опору фідерів та враховує специфіку роботи GFI. **Результати.** Встановлено, що режими ММ НН, приєднаних до системи розподілу, на інтервалах понад 60 с можна вважати квазі-стаціонарними, що дозволяє застосовувати статичні характеристики регулювання без урахування швидких перехідних процесів. Проаналізовано роботу моделі в режимах зниження реактивної потужності на вході мікромережі за допомогою PI-контролера та підтримки заданого значення реактивної потужності GFI. **Наукова новизна.** Розроблено нову розрахункову модель, використання якої, на відміну від існуючих, дозволяє виконати порівняння різних методів розподілу реактивної потужності між групою розосереджених джерел енергії та дослідити особливості локального регулювання напруги з використанням GFI. **Практична значимість.** З використанням розробленої моделі виконано аналіз та визначено залежності коефіцієнта droop-control по напрузі від значення реактивної потужності GFI та встановлені інтервали квазі-стаціонарності для потужності та напруги в ММ НН. З використанням розробленої моделі підтверджена ефективність локального регулювання напруги з використанням реактивної потужності GFI в різних режимах роботи мікромережі. Сформувано практичні рекомендації до налаштування параметрів GFI та швидкості передачі інформації в системах управління ММ НН. Бібл. 56, табл. 2, рис. 7.

Ключові слова: мікромережа, інтервали квазістаціонарності, мережеутворюючий інвертор, сонячна генерація, реактивна потужність.

Introduction. The development of electrical power grids and systems is currently driven by the integration of renewable energy sources (RES) and the formulation of control models [1] aligned with the Smart Grid concept [2]. One of the current research focuses in this field is the control of microgrid (MG) operating modes. MG connects a group of loads and distributed generation in a single controlled local object capable of operating both in the mode of connection to the electric power distribution system and in the isolated (island) mode [3, 4]. The terminology used in the paper is presented in [5]. The group of international IEC TS 62898 standards [6–9] defines the main options for building MGs and the features of their functioning.

Often, the MG includes electricity storage facilities [10] to accumulate its surplus for further use to balance demand within the MG and provide backup power during power outages. Electricity storage facilities affect the voltage regime in the networks [11]. In addition, the operation of electricity storage facilities as part of the MG allows optimizing the costs of purchasing electricity [12]. There are also possibilities for interaction between several inverters to exchange energy resources [13]. The possibilities of providing services for regulating the

distribution system modes by both a separate MG and a group of MGs [14] are expanding. The task of improving voltage levels and reducing losses in the network with RES is solved using various partitioning methods, in particular, shifting the current point of the flow to the partitioning site using available network power plants operating on RES [15]. Analysis of reactive power optimization in high-voltage power systems with the participation of transition system operators is presented in [16], while distribution system operators are considered in [17].

The main features of low-voltage (LV) MGs, according to definitions [7], include: short lengths and low resistance of feeders, small X/R ratios, a significant impact on the MG modes of RES generating capacities with unstable generation laws and electricity storage units, as well as the operation of the MG both synchronously with the electric grid (EG) and as isolated from the EG.

Connecting RES to the MG via converters results in the emergence of modes that are fundamentally different from the traditional modes of operation of local distribution systems. In particular, instead of a gradual voltage droop from the power center to electricity

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consumers, nodes with a local voltage increase at the points of connection of RES are formed in the LV MG. As a result, power flows arise in different directions in different periods of time in individual sections of the LV MG [18]. This significantly complicates the procedures for planning and controlling the modes of the LV MG operation. However, the main problem of ensuring the stability of the LV MG operation, especially in the island mode, is the absence of inertia of electromechanical processes in modern RES and inverters, which is inherent in synchronous generators of power plants and contributes to providing for the stability of electric power systems.

Today, the direction of local voltage regulation in MGs using reactive power of RES is actively developing in the world. At the same time, the problem of voltage regulation in LV MG is exacerbated by the practical use of remote control systems (MG controller) of grid-forming inverters (GFI) in conditions of limited data transfer rate. This justifies the need to create simulation models to determine the intervals of quasi-stationarity of low-voltage MG modes, which allows developing on their basis effective algorithms for reactive power regulation in LV MG of various composition, determining restrictions on the choice of the number of mode parameters taking into account their transfer rate.

One of the promising directions for solving this problem is to build a digital model that simulates the electromechanical processes of synchronous generators and generates the relative signals for controlling the LV MG mode. Means of control of the LV MG based on the models of synchronous generators are called grid-forming inverters (GFI) and allow to effectively regulate modes not only of the LV MG in the island mode but also increase the efficiency of control of modes of distribution systems. But at the same time there is an additional problem of creating means of simulating the GFI functions, taking into account the features of the electric grid structure in different modes in order to clarify the characteristics of such a digital model and build the laws of regulation for the LV MG control system.

Review of the literature. A description of modern developments in the field of the GFI simulating and analysis of the experience of operating such systems is provided in a number of review publications [19, 20]. For example, a comprehensive review of scientific and technical literature, which covers simulating methods, control methods, protection schemes, applications and actual implementations of the GFI. A large number of publications in scientific and technical literature detail individual components of the problem of building and using the GFI. The study [12] is devoted to the analysis of modern developments in the use of the GFI to maintain the stability and fault tolerance of power systems. Research shows that GFM control significantly outperforms grid-following inverter in stabilizing voltage, more robust support in low-inertia systems. Thus, different control approaches for grid-forming inverters are discussed and compared with the grid-forming properties of synchronous machines [21]. A comparative review of methods for simulating the operating modes of the MG with RES is provided in [22]. To solve the problems of simulating the MG functions and its individual components, software tools such as Pandapower, Matpower, Simulink and others are used. To conduct research on the impact of the GFI on the EG modes, standard EG test schemes with RES [23] have been developed.

There are various mathematical models for simulating the functions of a synchronous generator. For example, in [24], a virtual oscillator model based on the nonlinear Andronov-Hopf oscillator is studied. In [25], a model is provided for identifying the dynamic interaction of voltage and frequency values using the feedback effect. In [26], a unified sequence impedance model with harmonic linearization is presented, which characterizes multi-loop GFIs based on synchronous generator and virtual generator models.

However, a significant number of researchers prefer simplified simulation of the behavior of a synchronous generator without taking into account dynamic transient processes. Such important practical results of simulating the MG modes are obtained by simulating the continuous-time characteristics of the MG by analyzing quasi-stationary discrete states. For this purpose, the processes are simulated as a series of snapshots of the stationary states of the electrical grid without taking into account the transitional processes between them. For example, in [27], a method for analyzing processes in the MG without taking into account dynamic transient processes, which are microseconds to seconds, is presented. The equivalent scheme for calculations includes elements exclusively with linear characteristics. The simplification of mathematical models for the analysis of quasi-stationary states is carried out based on the following assumptions: it is assumed that the voltage and current graphs have a regular sinusoid, higher harmonics in the voltage and current graphs are not taken into account, in addition, electrical transient effects are not considered. The theoretical foundations of simulating quasi-stationary states in dynamic systems are covered in detail in [28].

In the study of voltage dynamics in real high and medium voltage networks, a 3rd order dynamic model of the power grid was built using DigSILENT PowerFactory software. The study showed a significant transient time of 15 s [29] in a real HV power grid. At the same time, there is no publication that would offer a method for analyzing voltage regulation processes within the day using a droop control method with local regulation in accordance with the requirements of the IEC TS 62898-3-1 standard [7] for the MG. Therefore, this publication considers the features of using quasi-stationary states in a daily optimization model of the MG functions with solar panels and an electricity storage unit according to the requirements of the IEC TS 62898-3-1 standard. The research was carried out using the PowerDynamics.jl tools [30]. Synthetic networks can be used to study the dynamic regimes of MG [31].

The goal of the paper is to determine the features of local voltage regulation in LV MG nodes connected to distribution systems, using the reactive power of GFIs installed in such LV MGs, using a newly developed imitation model in a unified package for analyzing the dynamics of energy systems with a significant share of RES. Such features within the article include the assessment of the dependence of the droop-control coefficient on the voltage on the value of the GFI reactive power, as well as the determination of quasi-stationarity intervals for power and voltage in LV MG in accordance with the requirements of international standards, which are determining parameters when developing algorithms for controlling the GFI reactive power in LV MG connected to the distribution system.

Features of using quasi-stationary states in simulating the GFI functions. The justification of the admissibility of using quasi-stationary states in simulating the GFI functions is given in [32]. For a quasi-stationary state with an interval $[t, t+1]$ at the beginning of the quasi-stationary interval in the node, there are voltage $V(t)$, power $S(t)$. A jump in power of in the node at time $t+1$ results in a transient process and setting of a new quasi-stationary state of the grid, new values of voltage in the node $V(t+1)$ and power $S(t+1)$. Therefore, for voltage control, quasi-stationary states of the grid are considered and fast transient processes are not taken into account, as shown in Fig. 1. Further, the processes of voltage control in the MG and optimization of mode parameters occur for a sequence of quasi-stationary states of the MG.

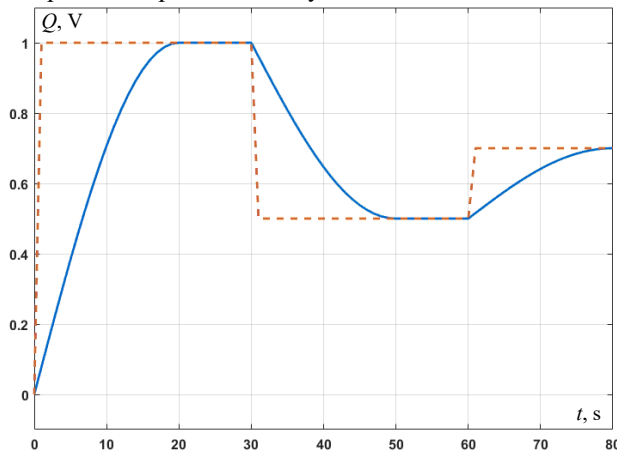


Fig. 1. Quasi-stationary states of the MG

At the same time, for calculations of the EG modes when forecasting the power of RES, imbalances [33] in power systems and optimal operation of electricity storage units, the models of the grids are used, which operate at 15- and 30-minute intervals that are represented in the form of quasi-stationary grid states. In particular, for voltage control with the specified time intervals of forecasting the power of renewable sources and loads, sequences of quasi-stationary grid states are used.

Objectives of voltage regulation in the MG by changing the reactive power in the GFI. In the problems of simulating the MG with the GFI, two alternative objectives of the MG voltage control may be used: minimizing the root mean square value of the voltages deviation in the MG nodes or maintaining the rated voltage value in the GFI connection node. Planning of the MG modes with minimization of the root mean square value deviation of the square value of the voltage of all MG nodes [34] or at the GFI setting node [35] is carried out by solving the problem of multi-criteria optimization of voltages in the nodes and minimizing the total value of active losses in the MG [34]. In [37], the “based on improved marine predator algorithm” is presented for solving such a multi-criteria optimization problem. The main advantage of planning the MG modes by solving the multi-criteria optimization problem is the complex equalization of voltages in all nodes of the electrical grid. However, to implement such a MG mode, it is necessary to monitor voltages in all controlled nodes with a measurement frequency of 0.1 s, which requires setting of a monitoring system with appropriate technical capabilities and significantly increases the cost of the MG mode control system.

For the analysis of the control of the MGs, useful data on the configuration of low-voltage networks and changes in loads over time are presented in [38]. Another source of data on the consumption of active power, voltage and current of the low-voltage network for a group of residential buildings recorded at intervals of 10 s is presented in [39]. Also, synthetic network models are useful for modeling voltage regulation in MGs [40]. The choice of MG operating modes from the point of view of the criterion of economic efficiency is presented in [41].

Therefore, the implementation of complex monitoring and voltage control systems requires a technical and economic justification. Another disadvantage of this approach is the low reliability of the MG mode control system. In order to implement the complex optimization systems task, operational information on voltages in all controlled MG nodes is required. In case of disappearance of operational information on voltages in individual MG nodes, the process of complex control of the MG modes is terminated.

Planning the MG modes with support for the rated voltage value in the GFI connection node allows avoiding the need for monitoring voltage in all nodes of the local electrical grid. This leads to a decrease in the cost of MG mode monitoring and control systems, as well as simplifying the control algorithms. Justification of the compliance of voltage values in uncontrolled nodes with permissible limits is carried out at the step of designing the electrical grid scheme. Features of the MG operation with control of voltage values in the GFI connection node are studied in [32].

In [42], a method of virtual voltage regulation for an isolated MG with a predominance of an active component of the resistance of power transmission lines is presented, taking into account the quadratic dependence between voltage and reactive power for MG with predominance of the inductive component. The proposed method provides for a more accurate reactive power response. The study [43] proposes to increase the accuracy of the inverter reactive power response based on virtual impedance. However, taking into account the virtual impedance of the MG significantly complicates the calculation model. One of the methods of voltage regulation using the fuzzy logic controller of the MATLAB package is presented in the study [44].

Normalization of the MG operating modes. The standard [7] defines the term “dynamic control in the MG” as transient disturbance control and dynamic disturbance control. Transient disturbance control suppresses disturbances in the MG caused by forced or unintentional sudden and strong changes in voltage and current due to switching of power sources or loads, configuration switching or troubleshooting. Transient processes last for milliseconds and are characterized by significant amplitudes and phase changes.

The MG control system has a hierarchical structure and is divided into 3 levels. When regulating the voltage, according to item 6.3.4.2 in [7], the primary control of the MG is based exclusively on local measurements, local calculations and local implementation and does not require a communication component. The standards [8, 9] describe the technical requirements that MGs and their operating scenarios must meet.

The main control elements of the MG according to item 3.3.1 [7] include: multi-level control functions implemented through a central controller for the overall stable operation of the system and individual local control

units for the output power of generating units and load consumption.

For the first level of the MG control system, voltage droop control is used. Voltage droop control is a process of linearizing the dependence of voltage and reactive power to minimize load transient processes, in most cases using a fixed coefficient:

$$V_{ref} = -K_0(Q - Q_0) + V'_0, \quad (1)$$

where V_{ref} is reference voltage of the grid; V'_0 is targeted (set) voltage of the grid; Q is the reactive power; Q_0 is preset reactive power; K_0 is constant voltage droop.

The secondary level of the MG control system has a slower dynamic response compared to the primary control due to the integration function. The voltage amplitude on the MG main bus is compared with the corresponding reference values and has the following form:

$$\delta V = K_{pV}(V_{ref} - V) + K_{iV} \int (V_{ref} - V) dt, \quad (2)$$

where δV is a voltage error, K_{pV} is the power regulation coefficient proportional to voltage; K_{iV} is the integration coefficient. The third level covers optimization processes, in particular voltage optimization in the MG nodes, minimization of the total reactive power of the sources, as well as minimization of reactive power at the MG input. The EN 50549-2 standard [45] defines the restraints on reactive power for voltage regulation in the range $[-0.484P_D, 0.484P_D]$, where $P_D = 0.9$ (Fig. 2).

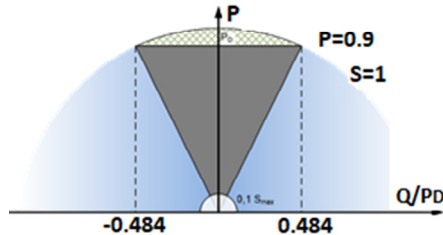


Fig. 2. Reactive power restraints [37]

At the same time, the IEC TS 62898-1 standard states: since the LV MG transmission lines have short length, there is no need to optimize the active losses in the MG.

The definition of “dynamic control” in the MG according to IEC TS 62898-1 is characterized by changes in amplitude and phase that go beyond the limits of normal operation and have a duration of up to seconds.

The EN 50549-2 standard, item 4.7.2.3.3 “Voltage-Related Control Mode” normalizes the integration constant of the first-order low-pass filter, which can be adjusted for at least 3 s. This means that when the reactive power jumps by 1 r.u., voltage output to the level of 0.95 of the new constant value occurs in 6.91 s. The range of adjustment of the constant integration of the first-order low-pass filter is also normalized for more than 3 s. Accordingly, the interval of voltage output at the level of 0.95 of the constant value is at least 6.91 s. Thus, depending on the constant integration of the first-order low-pass filter in the GFI device, when regulating the voltage using the reactive power of the GFI, the intervals of individual quasi-stationary states of the MG should exceed, respectively, the interval of voltage output at the level of 0.95 of the constant value from the range of 6.91 s.

Therefore, in this work, the optimization objective is limited to minimizing voltage deviations in the GFI connection node by changing the reactive power. In this case the system of constraints takes into account: the ranges of generation of active and reactive power of the

GFI, technical maximums of active and reactive power of the GFI, the maximum capacity and charge/discharge power of the energy storage unit [46–48].

Description of the LV MG model for experimental studies. For experimental studies, the PowerDynamics.jl tools were used. The tools are designed to simulate and analyze transient processes in electrical grids. In particular, a mathematical apparatus is provided for simulating a disturbance of one of the mode parameters [49], for example: a jump in active or reactive power of one load, a shutdown of one power transmission line, or other individual deviations of the initial parameters of the steady mode.

For simulating the GFI functions, the “MyDroopControl” component from the PowerDynamics.jl tool package was used. The block diagram of the GFI model is shown in Fig. 3. A detailed description of the functions of the “droop-control” block with a low-pass filter is provided in [50]. In the calculations, it is assumed that the GFI controls the solar station and the electric energy storage units connected to it.

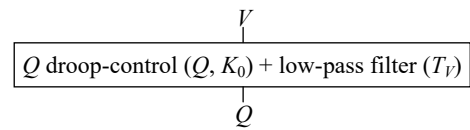


Fig. 3. GFI block diagram

Experimental calculations were performed for 0.4 kV radial electrical grid, which consists of 4 0.4 kV cable lines and 6 buses (Fig. 4). The phase shift value for the lines is $\tan \varphi = 0.24$, which allows to consider them as lines with predominantly active resistance.

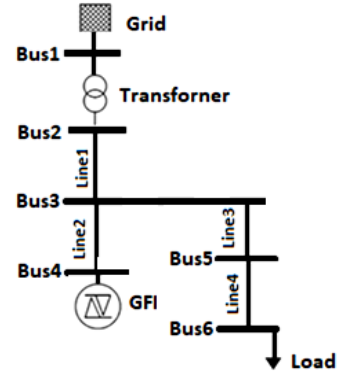


Fig. 4. LV MG diagram with the GFI

The GFI is connected to bus 4. When simulating the MG modes, the active and reactive power of the load connected to bus 6 is controlled. The MG is synchronized with the distribution system via an 11/0.4 kV 1000 kVA transformer. The main characteristics of the local grid are provided in the Table 1.

Table 1

Main characteristics of the MG

Parameters	Description	Length, km
HV/LV grid, kV	11.0 / 0.4	
Transformer	$P = 1$ MVA, voltage 11/0.4, $U_{sc} = 5.5\%$, $\Delta P_{sc} = 12$ kW	
ETL 1, 3	$R = 0.1649 \Omega/\text{km}$, $X = 0.04 \Omega/\text{km}$, $C_{pf} = 261$ pF/km, $I_{max} = 0.394$ kA	0.5
ETL 2, 4	$R = 0.1649 \Omega/\text{km}$, $X = 0.04 \Omega/\text{km}$, $C_{pf} = 261$ pF/km, $I_{max} = 0.394$ kA	0.05
Load	$\cos \varphi = 0.9$	

The voltage control function is simulated according to the requirements of [7]. The essence of the control is to generate inductive or reactive power proportional to the

difference between the voltage on the GFI bus and the predetermined voltage V_{ref} . The reactive power regulates the low-pass filter $q_{filters}$ which smoothes the oscillations of the signal and q_{droop} according to (1). The simulation of this principle is implemented in the model "Design, Operation, and Control of Remote Microgrid," modelName = "RemoteMicrogrid" from the MATLAB package. The GFI parameters for two options for constant integration of reactive power are presented in Table 2.

Table 2

GFI characteristics for experimental studies

	Option 1	Option 2
Rated power GFI, MVA	0.08	
Rated reactive power of GFI, MVar	0.0348	
Reference voltage of MG V_{ref} r.u.	0.985	
Low-pass filter, constant reactive power integration τ_r , s (time constant reactive power measurement)	3	12
Droop constant voltage droop coefficient K_O	0.1764	

The GFI model has the following restraints: reactive power according to EN-50549-2, active power of solar panels and energy storage unit are restrained by their datasheet parameters. The GFI model is implemented by a voltage source.

When simulating, it is assumed that the active and reactive power of the load at node 6, the active power of the solar panels, and the active power of the energy storage unit change during the day. The GFI, which converts the energy of the solar panels and of the storage unit, releases both active and reactive power to the MG.

When simulating, it is taken into account that according to the requirements of DSTU EN 50549-2, item 4.7.2.2, Note 4 [45], the GFI should be able to generate reactive power throughout the day.

The total number of simulation cycles of the MG modes with an interval of 60 s is 1440 cycles per day. The coefficient of load power on bus 6 is $\cos\varphi = 0.9$. The maximum load value is 231 kW. The maximum active power generated by the solar panels is 45 kW. The nominal GFI power is 80 kVA, the rated GFI reactive power is 34.5 kVar. Since it is planned to control the voltage at quasi-stationary intervals of 60 s, the hourly graphs are modified by linear interpolation of each time interval of 60 s and adding noise in the form of uniformly distributed random numbers in the range $[-0.01, 0.01]$ from the current power of the loads and the solar panel.

Analysis of the simulation results. In order to determine the quasi-stationary states of the LV MG with the GFI, an analysis of the dynamic disturbance in the LV MG with the predominance of the active component of the resistance of the transmission lines was carried out. The time interval in T_s of setting the LV MG to a steady state after a dynamic disturbance was determined. The voltage response in the LV MG nodes was analyzed, and a jump in the reactive power of the load in the remote MG bus 6 node was used as a disturbance. Figure 5 shows the dynamic mode of the process of changing the voltage in the GFI node to a new steady state with a jump in the reactive power of the load of 10 kVAR in the bus 6 node. The voltage response on the GFI bus is indicated by dots, the jump in the reactive power of the load in the bus 6 node is indicated by a solid line. The transfer function T_f (blue color) is used to estimate the jump. The quantization time interval is 0.1 s. The constant integration of the active power is restrained to the range of 3 to 12 s.

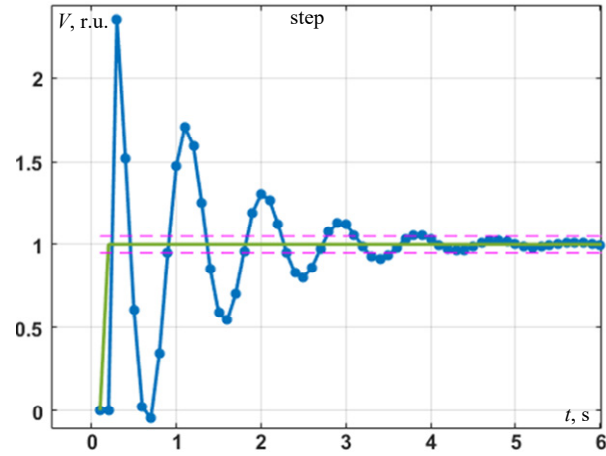


Fig. 5. Voltage response at node 4 during transients

After the jump in the reactive power of the load, the time interval of setting the voltage to a steady value in the range $[0.95, 1.05]$ is $T_s = 6.2$ s. The transfer function is:

$$T_f = \frac{24.09s^2 + 0.1587s + 0.1843}{s^3 + 9.278s^2 + 2.174s + 4.439}. \quad (3)$$

T_f has 3 poles and two zeros and corresponds to the low-pass filter. The transfer function was estimated by the *ttest* function of the MATLAB package [51]. Accuracy of the estimate: Status: Estimated using Estimate transfer function model *ttest* on time domain data; *Fit* to estimation data: 99.34 %, FPE: $1.361 \cdot 10^{-6}$, MSE: $1.282 \cdot 10^{-8}$. The accuracy of the transfer function estimate T_f is high. All poles of T_f are real and negative, therefore the system is stable.

Similar results of the time interval for setting T_s to a steady state after dynamic disturbances were obtained for all LV MG nodes, the maximum time for setting to a steady state $T_s \leq 6.2$ s.

It was established that for the pair "node voltage – GFI reactive power," taking into account the calculations and requirements of the standards, quasi-stationary states may be considered at intervals of 60 s, while the transient process during voltage regulation by controlling the GFI reactive power may not be considered.

Simulation of quasi-stationary states of the MG at a daily time interval was carried out with clock intervals of 60 s. Accordingly, the adopted interval of 60 s may be used for voltage regulation in the case of a daily forecast of consumption capacities, renewable sources and storage units. It should be noted that for research, parameters of modes of European electrical grids with intervals of 60 s, as well as 15 and 60 min are available.

Daily graphs of mode characteristics obtained based on the simulation results are shown in Fig. 6.

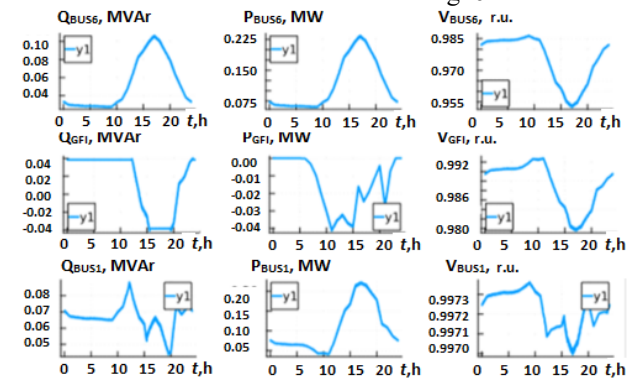


Fig. 6. Daily voltage and power graphs at controlled nodes

The GFI power restraints is 72 kW for active power, 34.8 kVA for reactive power in accordance with the rated GFI power and in accordance with the requirements of the EN 50549-2 standard. The effect of maintaining voltage at node 4 is achieved by regulating the reactive component of the GFI power. Thus, when the voltage at node 4 increases above the predetermined value, the value of the reactive component of the GFI power changes towards increasing inductance. When the voltage at node 4 droops below the predetermined value, the value of the reactive power component of the GFI changes towards increasing capacity. When using the GFI exclusively to maintain voltage at node 4, the reactive power component at node 1 (the node of connecting the MG to the distribution system) is not controlled. Therefore, if a Distribution System Operator imposes restraints on the values of the reactive power component at the input to the MG, such restraints should be additionally taken into account in the mathematical model.

The use of the GFI in the MG allows implementing additional useful functions, for which the MG modes were analyzed. Firstly, this is a reduction in reactive power and $\cos\varphi$ at the MG input, which refers to the third level of the MG control system. The objective is achieved using a PI controller [52] by selecting its parameters based on expert estimates. As a result of the GFI reactive power regulation, the reactive power at the distribution boundary of the LV MG and the MV EG is reduced. Accordingly, the MG reduces the payment for consumed or transmitted reactive power and reduces the flow of reactive power into an external EG. Secondly, based on the mutual agreement with a Distribution System Operator, it is possible to form a predetermined inductive or reactive power, taking into account maintaining the normalized voltage level in the MG. The results of the MG operation in different modes are presented in Fig. 7. It shows the following daily graphs: 1 is normal GFI operation; 2 is maximum GFI inductive power during the day; 3 is maximum GFI capacitive power during the day; 4 is the MG operation without the GFI; 5 is minimization of reactive power at the distribution boundary of the LV MG and MV ES using a PI-regulator.

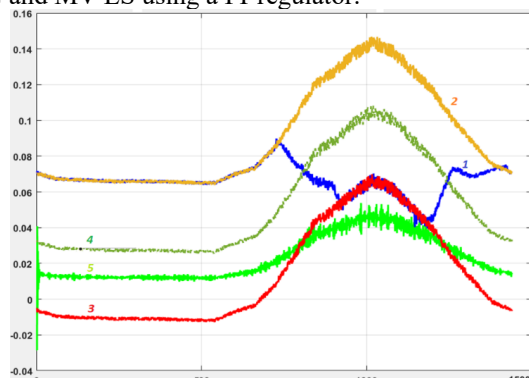


Fig. 7. Reactive power at the MG input for different modes of GFI reactive power control

As a result, the model proposal can provide reactive power control for one of the modes – constant power factor $\cos\varphi$, reactive power as a function of active power $Q(P)$, fixed reactive power Q_{fix} .

Thus, the proposed new model allows for a specific LV MG connected to the distribution system, indirectly through the estimation of the transfer function coefficients to determine the quasi-stationarity intervals, as well as to vary the value of the droop control coefficient in order to optimize

its value. At the same time, the operating parameters of the LV MG meet the requirements of the standards for LV MG. For specific LV MGs, the model generates the parameters necessary for the subsequent creation of an optimal voltage or reactive power control system.

Discussion. During the experimental studies, a tool was developed for estimating methods of voltage regulation and optimization in the MG, taking into account the requirements of standards for the MG such as restraints on active and reactive power of the GFI and energy storage systems. The ability of the PowerDynamics.jl tools to perform simulation of the LV MG modes with a significant number of nodes, in particular using standard LV, MV and MG groups connected to the MV grid, was confirmed.

The provided model allows optimizing the LV MG voltage profile by selecting the droop control coefficient KQ when using the day-ahead forecast of consumption capacities, generation from renewable sources and characteristics of electricity storage systems. The provided model allows solving the problem of selecting the optimal value of the droop control coefficient for a specific MG mode. The optimal values of this coefficient may be determined in the problems of reactive power distribution in the RES group [53], as well as in the problems of interpolation by a sequence of linear segments of droop control coefficients to improve the efficiency of voltage regulation in the MG [39]. The conclusion on the admissibility of using quasi-stationary state models with a discreteness of 60 s for simulating modes and analyzing the MG states allows taking into account retrospective information on the modes of electrical grids provided in particular in [54]. The use of such retrospective information allows verifying the MG control methods and models, as well as performing machine learning of artificial intelligence tools that may be used in solving individual problems of controlling the MG modes.

To enhance the responsiveness and efficiency of voltage control strategies in LV MGs, the integration of digital twin technology offers a promising direction. A digital twin constitutes a dynamic, data-driven virtual representation of the physical energy system, capable of real-time synchronization with sensor data and predictive modeling. Recent work [16] demonstrated the feasibility of applying digital twin architecture for increasing the operational efficiency of RES through predictive analytics and real-time system monitoring.

The developed model will allow further simulating of simultaneous local voltage regulation by several GFIs, which meets the requirements of primary local voltage regulation provided in the IEC TS 62898-1 standard. The provided LV MG model allows comparing methods of proportional power distribution between MG energy sources, in particular with an energy storage unit.

Another expected use of the developed MG model is aimed at selecting optimal parameters, for example, of a PI controller in order to regulate reactive power at the MG input. The latter requires additional research on the comparison of the use of PI reactive power regulation and other methods for reducing reactive power at the MG input. In particular, it is possible to analyze the change in MG parameters when the inertia of LV MG changes [55].

The obtained results of voltage transfer function modeling are useful in developing an improved reactive power control system for a LV MG connected to the distribution network [56].

Conclusions. A new imitation model has been developed for analyzing the dynamics of voltage and reactive power in LV MG connected to the distribution network, with a predominant active component of resistance in the feeders connecting load nodes and GFIs in accordance with the requirements of modern standards. Using the model allows to analyze and determine the dependence of the droop-control coefficient on the voltage on the value of the GFI reactive power and the quasi-stationarity intervals for power and voltage in the LV MG, which are the determining parameters for the development of algorithms for remote control of the GFI reactive power with limited-speed information transmission systems in the LV MG.

The peculiarities of local voltage control in the LV MG connected to the distribution network include intervals of quasi-stationarity of voltage. The transfer function for the dependence of the voltage at the nodes on the reactive power of the load and the transient process setting time was estimated. It is shown that the LV MG modes at intervals of more than 60 s may be considered quasi-stationary, which allows voltage droop control to be used when regulating the voltage and not taking into account fast transient processes.

The intervals of individual quasi-stationary states of the LV MG were determined to exceed the intervals of the relative output voltage at a level of 0.95 of the constant value. An example of voltage regulation at quasi-stationary intervals of 60 s is shown. The established quasi-stationarity intervals confirmed the possibility of using a limited-speed data transmission system in LV MG.

The model operation in the reactive power reduction mode at the MG input using a PI controller and for generating a predetermined reactive power at the MG input is analyzed.

The constructed model allows creating practical requirements for setting the voltage droop control GFI value. Examples of using the model in the implementation of local voltage and reactive power regulation in the MG with RES are provided, taking into account changes in their operating parameters, namely: when choosing the optimal parameters of the PI controller in order to reduce reactive power at the MG input; when generating the predetermined reactive power at the MG input. The provided model is intended for simulating the processes of voltage regulation of the LV MG, in particular when using the forecast of load power, electricity supply from RES, and existing parameters of the storage system. The developed model is the basis for its further development in order to build control systems for the GFI reactive power regulation in the MG.

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Conflict of interest. The authors declare that they have no conflicts of interest.

REFERENCES

1. Blinov I.V., Trach I.V., Parus Y.V., Derevianko D.G., Khomenko V.M. Voltage and reactive power regulation in distribution networks by the means of distributed renewable energy sources. *Tekhnichna Elektrodynamika*, 2022, no. 2, pp. 60-69. doi: <https://doi.org/10.15407/techned2022.02.060>.
2. IEC Technical Report 63097. *Smart grid standardization roadmap*. 2017. 315 p. Available at: <https://webstore.iec.ch/en/publication/27785>.
3. Denysiuk S., Derevianko D. Optimisation features of energy processes in energy systems with Distributed Generation. *2020 IEEE 7th International Conference on Energy Smart Systems (ESS)*, 2020, pp. 211-214. doi: <https://doi.org/10.1109/ESS50319.2020.9160212>.
4. NEURC on approval of the transmission system code. 2018. Available at: <https://zakon.rada.gov.ua/laws/show/v0309874-18#Text>.
5. IEC 60050 – *International Electrotechnical Vocabulary* – Details for IEV number 617-04-22: 'microgrid'.
6. IEC TS 62898-1: 2017+AMD 1: 2023 *Microgrids – Part 1: Guidelines for microgrid projects planning and specification*. 2023. 78 p.
7. IEC TS 62898-3-2. *Microgrids – Part 3-2: Technical requirements – Energy management systems*. 2024. 74 p.
8. IEC TR 62898-4 *Microgrids – Part 4: Use cases*. 2023. 70 p.
9. IEC TS 62898-3-4. *Microgrids – Part 3-4: Technical requirements – Microgrid monitoring and control systems*. 2023. 40 p.
10. Parus Y.V., Blinov I.V. Optimization of the use of available energy resources of the microgrid under the condition of supporting readiness for isolated mode. *Tekhnichna Elektrodynamika*, 2025, no. 5, pp. 56-69. doi: <https://doi.org/10.15407/techned2025.05.056>.
11. Kyrylenko O.V., Blinov I.V., Parus E.V., Trach I.V. Evaluation of efficiency of use of energy storage system in electric networks. *Tekhnichna Elektrodynamika*, 2021, no. 4, pp. 44-54. doi: <https://doi.org/10.15407/techned2021.04.044>.
12. Blinov I., Radziukynas V., Shymaniuk P., Dyczko A., Stecula K., Sychova V., Miroshnyk V., Dychkovskiy R. Smart Management of Energy Losses in Distribution Networks Using Deep Neural Networks. *Energies*, 2025, vol. 18, no. 12, art. no. 3156. doi: <https://doi.org/10.3390/en18123156>.
13. Al Kez D., Foley A., Ahmed F. Exploring Transient Voltage and Frequency Responses in Low Inertia Power Systems: A Comparative Study of Grid Following and Grid Forming Battery Energy Storage Systems. *SSRN Electronic Journal*, 2023. doi: <https://doi.org/10.2139/ssrn.451229256>.
14. Abu-El-Haija L., et. al. Multi-microgrid system optimization addressing the uncertainties in generation and load demand. *IEEE Access*, 2025, vol. 13, pp. 62165-62178. doi: <https://doi.org/10.1109/ACCESS.2025.3555927>.
15. Lakshmi G.S., Rubanenko O., Hunko I. Control of the Sectioned Electrical Network Modes with Renewable Energy Sources. *2021 International Conference on Sustainable Energy and Future Electric Transportation (SEFET)*, 2021, pp. 1-6. doi: <https://doi.org/10.1109/SeFet48154.2021.9375781>.
16. Sachan S., Mishra S., Øyvang T., Bordin C. Reactive Power Observability for Improved Voltage Stability and Loadability: A Detailed Review. *Johnson Matthey Technology Review*, 2025, vol. 69, no. 4, pp. 503-518. doi: <https://doi.org/10.1595/205651325X17458327898748>.
17. Belik M., Rubanenko O. Implementation of Digital Twin for Increasing Efficiency of Renewable Energy Sources. *Energies*, 2023, vol. 16, no. 12, art. no. 4787. doi: <https://doi.org/10.3390/en16124787>.
18. Bouhadouza B., Sadaoui F. Optimal power flow analysis under photovoltaic and wind power uncertainties using the blood-sucking leech optimizer. *Electrical Engineering & Electromechanics*, 2025, no. 6, pp. 15-26. doi: <https://doi.org/10.20998/2074-272X.2025.6.03>.
19. Traupmann A., Kienberger T. Test Grids for the Integration of RES – A Contribution for the European Context. *Energies*, 2020, vol. 13, no. 20, art. no. 5431. doi: <https://doi.org/10.3390/en13205431>.
20. Song G., Cao B., Chang L. Review of Grid-forming Inverters in Support of Power System Operation. *Chinese Journal of Electrical Engineering*, 2022, vol. 8, no. 1, pp. 1-15. doi: <https://doi.org/10.23919/CJEE.2022.000001>.
21. Unruh P., Nuschke M., Strauß P., Welck F. Overview on Grid-Forming Inverter Control Methods. *Energies*, 2020, vol. 13, no. 10, art. no. 2589. doi: <https://doi.org/10.3390/en13102589>.
22. Prabaksorn T., Naayagi R., Lee S.S. Modelling and Simulation of Microgrid in Grid-Connected Mode and Islanded Mode. *2020 2nd International Conference on Electrical, Control and Instrumentation Engineering (ICECIE)*, 2020, pp. 1-8. doi: <https://doi.org/10.1109/ICECIE50279.2020.9309649>.
23. PandaPower. Available at: <https://pandapower.readthedocs.io/en/latest>.
24. Lu M. Virtual Oscillator Grid-Forming Inverters: State of the Art, Modeling, and Stability. *IEEE Transactions on Power Electronics*, 2022, vol. 37, no. 10, pp. 11579-11591. doi: <https://doi.org/10.1109/TPEL.2022.3163377>.
25. Yang Y., Xu J., Li C., Zhang W., Wu Q., Wen M., Blaabjerg F. A new virtual inductance control method for frequency stabilization of grid-forming virtual synchronous generators. *IEEE Transactions on Industrial Electronics*, 2023, vol. 70, no. 1, pp. 441-451. doi: <https://doi.org/10.1109/TIE.2022.3148749>.
26. Elshenawy M.A., Radwan A., Mohamed Y.A.-R.I. Unified Sequence Impedance Models of Synchronous Generator-and Virtual Oscillator-Based Grid-Forming Converters. *IEEE Transactions on Power*

Delivery, 2024, vol. 39, no. 1, pp. 56-70. doi: <https://doi.org/10.1109/TPWRD.2023.3321699>.

27. Kovacs A. *Full-scope simulation of grid-connected microgrids*. CIGRE session 2018, Paris, France. Available at: <https://www.ecigre.org/publications/detail/c6-304-2018-full-scope-simulation-of-gridconnected-microgrids.html>.

28. Burton T.D. *Introduction to dynamic systems analysis*. McGraw-Hill Publ., 1994. 690 p.

29. Nnoli K.P., Delic F., Kettemann S. Transient Dynamics and Propagation of Voltage and Frequency Fluctuations in Transmission Grids. *IEEE Access*, 2023, vol. 11, pp. 11307-11328. doi: <https://doi.org/10.1109/ACCESS.2023.3241014>.

30. Plietzs A., Kogler R., Auer S., Merino J., Gil-de-Muro A., Liße J., Vogel C., Hellmann F. PowerDynamics.jl – An experimentally validated open-source package for the dynamical analysis of power grids. *SoftwareX*, 2022, vol. 17, art. no. 100861. doi: <https://doi.org/10.1016/j.softx.2021.100861>.

31. Büttner A., Plietzs A., Anvari M., Hellmann F. A framework for synthetic power system dynamics. *Chaos*, 2023, vol. 33, no. 8, art. no. 083120. doi: <https://doi.org/10.1063/5.0155971>.

32. El Helou R., Kalathil D., Xie L. Fully Decentralized Reinforcement Learning-Based Control of Photovoltaics in Distribution Grids for Joint Provision of Real and Reactive Power. *IEEE Open Access Journal of Power and Energy*, 2021, vol. 8, pp. 175-185. doi: <https://doi.org/10.1109/OAJPE.2021.3077218>.

33. Blinov I., et. al. Advanced long short-term memory-based forecasting of electricity imbalances in the Ukrainian power system: Enhancing accuracy and stability with comparative model analysis. *Energy Exploration & Exploitation*, 2025, pp. 1-25. doi: <https://doi.org/10.1177/01445987251360272>.

34. Baudette M., Sankur M.D., Breaden C., Arnold D., Callaway D.S., MacDonald J. Implementation of an Extremum Seeking Controller for Distributed Energy Resources: Practical Considerations. *2020 IEEE Power & Energy Society General Meeting (PESGM)*, 2020, pp. 1-5. doi: <https://doi.org/10.1109/PESGM41954.2020.9281991>.

35. Fang Y., Yang J., Jiang W. Optimal Scheduling Strategy of Microgrid Based on Reactive Power Compensation of Electric Vehicles. *Energies*, 2023, vol. 16, no. 22, art. no. 7507. doi: <https://doi.org/10.3390/en16227507>.

36. Brandao D.A.de L., Callegari J.M.S., Brandao D.I., Pires I.A. Coordinated, Centralized, and Simultaneous Control of Fast Charging Stations and Distributed Energy Resources. *Inventions*, 2024, vol. 9, no. 2, art. no. 35. doi: <https://doi.org/10.3390/inventions9020035>.

37. Qiu J., Lan D., Zhang Y., Li H. Multi-objective reactive power optimization for low voltage distribution networks based on improved marine predator algorithm. *Journal of Physics: Conference Series*, 2024, vol. 2703, no. 1, art. no. 012050. doi: <https://doi.org/10.1088/1742-6596/2703/1/012050>.

38. Meinecke S., et. al. General planning and operational principles in German distributions systems used for Simbench. *25th International Conference on Electricity Distribution*, 2019, art. no. 0139.

39. Athanasoulas S., Guasselli F., Doulamis N., Doulamis A., Ipiotis N., Katsari A., Stankovic L., Stankovic V. The Plegma dataset: Domestic appliance-level and aggregate electricity demand with metadata from Greece. *Scientific Data*, 2024, vol. 11, no. 1, art. no. 376. doi: <https://doi.org/10.1038/s41597-024-03208-0>.

40. Lindner M., et. al. Aktuelle Musternetze zur Untersuchung von Spannungsproblemen in der Niederspannung. *14. Symposium Energieinnovation*, 10. bis 12. Februar 2016. Available at: https://www.tugraz.at/fileadmin/user_upload/Events/Eninnov2016/files/kf/Session_E2/KF_Aigner.pdf. (Ger).

41. Blinov I.V., Parus Y.V., Shymaniuk P.V., Vorushylo A.O. Optimization model of microgrid functioning with solar power plant and energy storage system. *Tekhnichna Elektrodynamika*, 2024, no. 5, pp. 69-78. doi: <https://doi.org/10.15407/teched2024.05.069>.

42. Vaishnav V., Sharma D., Jain A. Quadratic-Droop-Based Distributed Secondary Control of Microgrid With Detail-Balanced Communication Topology. *IEEE Systems Journal*, 2023, vol. 17, no. 3, pp. 3401-3412. doi: <https://doi.org/10.1109/JSYST.2023.3240171>.

43. Vilorio E.A.M., Becerra J.E.C., Durán D.E.S. Virtual voltage control to redistribute reactive power of generators in a microgrid. *International*

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Journal of Power Electronics and Drive Systems (JPEDS), 2024, vol. 15, no. 2, pp. 784-792. doi: <https://doi.org/10.11591/jpedsv15.i2.pp784-792>.

44. Adiche S., Larbi M., Toumi D. Optimizing voltage control in AC microgrid systems with fuzzy logic strategies and performance assessment. *Electrical Engineering & Electromechanics*, 2025, no. 3, pp. 11-17. doi: <https://doi.org/10.20998/2074-272X.2025.3.02>.

45. EN 50549-2 *Requirements for generating plants to be connected in parallel with distribution networks - Part 2: Connection to a MV distribution network - Generating plants up to and including Type B*.

46. NEURC Resolution "On Approval of Distribution Network Code" no. 310, 14.03.2018.

47. NEURC's Resolution "On Approval of Retail Market Rules" no. 312, 14.03.2018.

48. NEURC's Resolution "On Approval of the Commercial Electricity Metering Code" no. 311, 14.03.2018.

49. Kittel T., Auer S., Horn C. Sneak Preview: PowerDynamics.jl An Open-Source library for analyzing dynamic stability in power grids with high shares of renewable energy. *ArXiv.org*, 2020. doi: <https://doi.org/10.48550/arXiv.2012.05175>.

50. Liu Z., Majidi M., Wang H., Mende D., Braun M. Time Series Optimization-Based Characteristic Curve Calculation for Local Reactive Power Control Using Pandapower-PowerModels Interface. *Energies*, 2023, vol. 16, no. 11, art. no. 4385. doi: <https://doi.org/10.3390/en16114385>.

51. *Statistics and machine learning toolbox*. The MathWorks Inc. 2022. Available at: <https://www.mathworks.com/help/ident/ref/tfest.html>.

52. Al Sumarnad K.A., Sulaiman N., Wahab N.I.A., Hizam H. Energy Management and Voltage Control in Microgrids Using Artificial Neural Networks, PID, and Fuzzy Logic Controllers. *Energies*, 2022, vol. 15, no. 1, art. no. 303. doi: <https://doi.org/10.3390/en15010303>.

53. Hussaini H., Yang T., Gao Y., Wang C., Dragicevic T., Bozhko S. Droop Coefficient Design in Droop Control of Power Converters for Improved Load Sharing: An Artificial Neural Network Approach. *2021 IEEE 30th International Symposium on Industrial Electronics (ISIE)*, 2021, pp. 1-6. doi: <https://doi.org/10.1109/ISIE45552.2021.9576482>.

54. Meinecke S., Sarajlić D., Drauz S.R., Klettke A., Lauven L.-P., Rehtanz C., Moser A., Braun M. SimBench – A Benchmark Dataset of Electric Power Systems to Compare Innovative Solutions Based on Power Flow Analysis. *Energies*, 2020, vol. 13, no. 12, art. no. 3290. doi: <https://doi.org/10.3390/en13123290>.

55. Ahmed F., Al Kez D., McLoone S., Best R.J., Cameron C., Foley A. Dynamic grid stability in low carbon power systems with minimum inertia. *Renewable Energy*, 2023, vol. 210, pp. 486-506. doi: <https://doi.org/10.1016/j.renene.2023.03.082>.

56. Blinov I., Trach I., Miroshnyk V. Local reactive power control in a low-voltage microgrid using a 4th-order IIR filter. *Vidnovlunava Energetika*, 2025, no. 4, pp. 42-58. doi: [https://doi.org/10.36296/1819-8058.2025.4\(83\).42-58](https://doi.org/10.36296/1819-8058.2025.4(83).42-58).

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I. Trach¹, PhD, Senior Researcher,
M. Belik², D.Tech.Sc., Leading Researcher,
O. Rubanenko^{3,4,5}, D.Tech.Sc., Senior Researcher,
V. Miroshnyk¹, Senior Researcher,

I. Blinov¹, D.Tech.Sc., Leading Researcher,
¹ Institute of Electrodynamics of NAS of Ukraine,
56, Beresteysky Avenue, Kyiv, 03057, Ukraine,
igor.trach@gmail.com (Corresponding Author)

² Department of Electrical Power Engineering,
University of West Bohemia,
Univerzitní 26, Pilsen, 30614, Czech Republic.

³ Research and Innovation Center for Electrical Engineering (RICE),
Faculty of Electrical Engineering of the University of West
Bohemia, Univerzitní 26, Pilsen, 30614, Czech Republic.

⁴ Institute of Renewable Energy,

20-a, Hnata Khotkevych Str., Kyiv, 02094, Ukraine.

⁵ Vinnitsya National Technical University,

95, Khmelnytsky Highway, Vinnitsya, 21021, Ukraine.