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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT OF INTELLIGENT CONTROL SYSTEM FOR POWER CONVERTERS

Specialty: **3337.01–Information-measurement and control systems**

(by fields)

Field of science: **Technical sciences**

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Baku - 2024

The work was performed at the Instrumentation Engineering department of Azerbaijan State Oil and Industry University.

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GENERAL CHARACTERISTICS OF THE WORK

Relevance and development of the topic. Rapidly increasing energy demand, the extent of damage caused by traditional energy sources to the environment, and the fact that these sources are about to be exhausted have aroused special interest in renewable energy sources. Solar energy is one of the most promising renewable energy sources and has high prospects. Solar energy is converted into electricity by means of modules composed of photovoltaic elements made of special semiconductor materials. However, the fact that the output voltage of photovoltaic modules depends on factors such as solar energy intensity and temperature makes it necessary to connect them to the load circuit by means of special constant current power converters to ensure the stability of the output voltage at a given reference value. The main task of DC power converters is to ensure the stability of the output voltage in a certain variation range of the input voltage and load current. DC converters are connected to photovoltaic modules within small autonomous electrical networks called microgrids. DC converters connected to photovoltaic modules are usually connected in a parallel structure with their outputs connected to a common main DC bus.

The relative complexity of existing control systems, weak structural and functional connection between local-local and local-superior levels of control, the need for human intervention at different levels of control, poor adaptability under conditions of various influencing factors, stability and energy losses are the biggest shortcomings of these control systems. There is a need to establish an intelligent central control system that organizes the energy exchange between the internal functional blocks of the microgrid, as well as with other electrical networks of this microgrid, and minimizes energy losses.

The object and subject of the research. The object of the dissertation is DC-DC converters in DC microgrids and a microgrid built from these converters. The subject of the dissertation is the development of the intelligent control system of the microgrid.

Research goals and objectives. The main goal of the dissertation work is the development of an intelligent control system that allows minimizing human intervention at different levels of control in DC microgrids composed of power electronics converters under various internal and external influences. The main tasks of the dissertation work are the following:

1) Ensuring the autonomous, adaptive and stable operation mode of the microgrid in conditions of uncertainty ;
2) Solving the issues of photovoltaic maximum power extraction;
3) Solving power distribution issues between DC power electronics converters;
4) Solving optimal control issues between renewable energy sources, energy storage modules and other electrical networks in microgrids;
5) Developing a new structural-functional model of the intelligent information-measurement and control system of the microgrid.

Research methods. Metaheuristic optimization methods, measurement and error theory, nonlinear control, virtual resistance method, algorithms for obtaining maximum power from photovoltaic modules, and automatic regulation theory were used in the dissertation. Computer simulations were carried out in MATLAB and SIMULINK environment.

Main issues for review. The following provisions are submitted for defense in the dissertation work:

-Minimization of standard deviation in converter output currents and bus voltage errors for optimal control;

-Development of the intelligent PID controller at all three levels of microgrid control;

- Development of a new method for extracting the maximum output power based on measurement results of the photovoltaic modules under the influence of the half shading physical phenomenon in DC microgrids;

-Development of a new functional model of the intelligent control system that optimally solves the problems of continuous energy supply of load circuits in DC microgrids.

Scientific novelty of the research. The main scientific innovations of the study are as follows:

- For the first time, the issue of minimization of standard deviation in DC-DC converter output currents and DC bus voltage errors was solved by the intelligent metaheuristic MOTH-FLAME algorithm for optimal control [5, 6];
- In order to improve the output characteristics of PV-DC power converters with nonlinear characteristics, the development issue of the intelligent PID controllers at different levels of control was solved [1-4];
- Based on the measurement results of photovoltaic modules , a new method of tracking the maximum power point with the metaheuristic MOTH-FLAME algorithm, which allows obtaining the maximum output power, has been developed [5, 7, 8];
- A novel control system, which has the ability to perform optimal energy exchange with other microgrids or the state power grid, has been developed for the uninterrupted load supply in DC microgrids [10,12,15]. .

The theoretical and practical significance of the research . The obtained main results have important theoretical and applied significance.

The theoretical importance of the work - the structural and functional models of the microgrid intelligent information-measurement and control system were developed in the dissertation work; new methods of optimizing microgrid control methods with the metaheuristic MOTH-FLAME algorithm were developed and presented; The selection methodology of the corresponding power converters for the intelligent control system development for DC microgrid is given; state equations, transfer functions, as well as the mathematical model of circulating currents of these converters were obtained. The presented methods and models are universal in nature and are of particular importance from the point of view of continuing theoretical research in this field.

The practical importance of the work – the proposed intelligent control system can be used for remote measurement and control stations, seismic, telecommunication and meteorological stations, biomedical equipment, remote residential and medical centers, smart cities and villages, electric cars, drones, ships and other moving objects. or can be successfully applied in solving the problems of complete power supply.

Approbation and application. The main research and practical results of the dissertation were applied in the lecture and laboratory classes of the subjects such as "Intelligent measurement tools in computer-information measurment systems", "Electronics and schematic engineering" taught at the "Instrumentation Engineering" department of the Azerbaijan State Oil and Industry University. Its scientific-research application was approved by the application act. The main results of the dissertation were discussed at the following international conferences: International Conference Automatics and Informatics (ICAI-2021), 30 Sept.-2 Oct. 2021, Varna, Bulgaria ; International Scientific and Practical Conference «Intellectual Systems and Information Technologies», September 13–19, 2021, Odesa, Ukraine; International Conference Automatics and Informatics (ICAI-2022), 6-8 Oct. 2022, Varna, Bulgaria; The third international scientific-practical conference - Modern Information , Measurement, and Control systems: problems, applications and perspectives (MIMCS-2022), November 04-05, 2022, Antalya, Turkey; IFAC Workshop on Control for Smart Cities (CSC 2022), 27–30 June 2022, Sozopol, Bulgaria; International Conference on Electronics, Engineering Physics and Earth Science (EEPES 2023), June 21-23, 2023, Kavala, Greece; International Conference on Industry Sciences & Computer Sciences Innovation (iSCSi'23), October 04-06, 2023, Lisbon, Portugal.

15 scientific works, including 8 articles, 7 scientific-conference materials, 2 articles without co-authors, corresponding to

the topic of the dissertation work, were published. Of these, 8 are indexed in "SCOPUS" and 1 in "Web of Science" scientific databases.

The dissertation is realized at: Dissertation work Ministry of Science and Education of the Republic of Azerbaijan, Azerbaijan State Oil and Industry University, Department of "Instrumentation Engineering".

Personal involvement of the author: The purpose of the dissertation work, the propositions defended, comparative analyses, the developed new intelligent method and structural-functional models , the performed mathematical calculations, the design of schemes, the obtained simulation and experimental results belong to the author personally.

Scope and structure of the dissertation: The dissertation was written in accordance with the requirements set by the Supreme Attestation Commission under the President of the Republic of Azerbaijan. The dissertation consists of an introduction, three chapters, a conclusion and cited literature.

The introduction of the dissertation is 32059, chapter I 73283 characters, chapter II 40834 characters, chapter III 51959 characters, the result is 2292 characters and the text is interpreted in a total of 200427 characters.

BRIEF CONTENT OF THE CASE

In the introduction , the relevance of the subject area, the goals and objectives of the research, the main propositions defended, research methods, and the theoretical and practical significance of the research are mentioned.

In Chapter 1, a broad classification of power converters was carried out, their main types were studied in a comparative form, unidirectional SEPIC circuit converters were selected for connection to PV modules, bidirectional SEPIC-ZETA converters were selected for the interface with the battery, and metaheuristic MOTH-FLAME was selected for the development of an intelligent control system. MOTH-FLAME optimization method was selected, their state-space equations and transfer functions were obtained. A comparative analysis of power converter regulation methods is also given here.

Figure 1shows the structural model of DC microgrids.

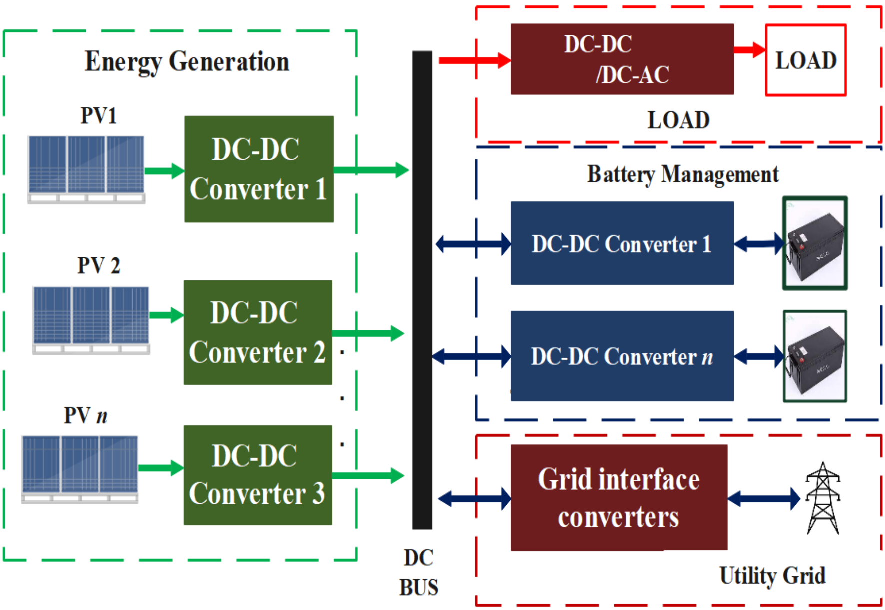

Figure 1. Structural model of DC microgrids

A microgrid is a small, self-contained electrical network consisting of power sources, load circuits, and power electronics converters. The main task of DC-DC power converters is to control the DC bus voltage and power according to the signals from the controller. Figure 2 shows the connection scheme of the unidirectional SEPIC converter to the PV module and the bus.

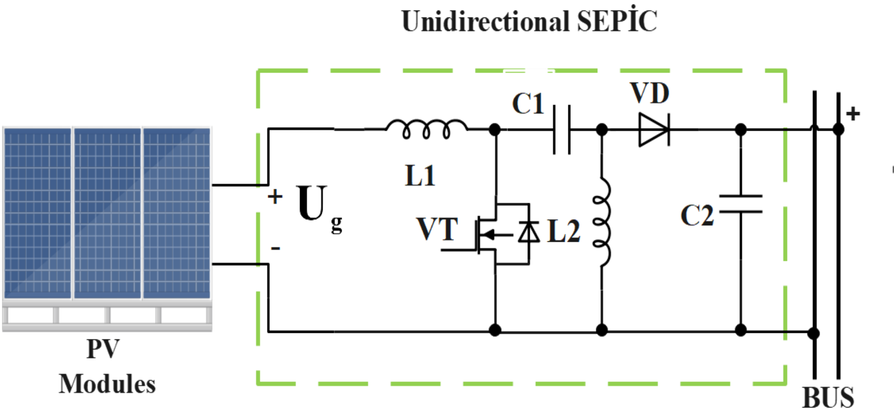

Figure 2. Connection of SEPIC to PV module and bus

Due to the ability to produce larger or smaller output voltages compared to the input voltage, no pulsating load current, non-inverting output voltage, and higher useful duty factor, SEPIC type unidirectional DC-DC converters have been chosen as unidirectional inverters to connect to PV modules.

The generalized state equations of SEPIC type unidirectional DC-DC converters were obtained by combining the dynamic equations characterizing the closed and open modes of the transistors operating in the electronic switch mode in these converters in a generalized mathematical model. The generalized state equations of the SEPIC type unidirectional DC-DC converters are shown by the mathematical expression given below:

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{du_{C1}}{dt} \\ \frac{du_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-(1-d)}{L_1} & \frac{-(1-d)}{L_1} \\ 0 & 0 & \frac{d}{L_2} & \frac{-(1-d)}{L_2} \\ \frac{(1-d)}{C_1} & \frac{-d}{C_1} & 0 & 0 \\ \frac{(1-d)}{C_2} & \frac{(1-d)}{C_2} & 0 & \frac{-1}{RC_2} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ u_{C1} \\ u_{C2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} [U_g], \quad (1)$$

$$\mathbf{Y} = [0\ 0\ 0\ 1] \begin{bmatrix} i_{L1} \\ i_{L2} \\ u_{C1} \\ u_{C2} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} U_g. \quad (2)$$

Here, $i_{L1}$and are $i_{L2}$the inductive coil currents, $u_{C1}$and u_{C2} the voltage drops across the capacitors, $U_g$the input voltage, *d* and 1- *d* are the charge factors, which characterize the closed and open switching modes of the transistor.

Using the equations of state, it is possible to obtain the value of the charge coefficient, which characterizes the duration of the pulse given to the transistor of the SEPIC converter, and the transfer function that relates the output voltage. Values of inductor *L1* and *L2* are 3.6mH, values of capacitor *C1* and *C2* are 19mF, load resistance is 5 Om is selected. Taking into account the data, the following transfer functions were obtained :

$$\frac{U_{out}(s)}{d(s)} = \frac{-1.74*10^{-7}s^3+4*10^{-5}s^2-0.0018s+0.5887}{1.3*10^{-9}s^4+2*10^{-8}s^3+1.8*10^{-5}s^2+1.7*10^{-4}s+0.05}. \quad (3)$$

$$\frac{U_{out}(s)}{U_{in}(s)} = \frac{1.3*10^{-4}s^2+1.4}{1.5*10^{-8}s^4+2.5*10^{-7}s^3-2*10^{-4}s^2+0.002s+1.4*10^{-4}}. \quad (4)$$

In this chapter, traditional optimization methods and intelligent metaheuristic optimization methods are also analyzed comparatively. It was determined that metaheuristic algorithms have the following advantages in building the intelligent control system of DC microgrids:

1. Having self-learning mechanisms ;
2. Having the ability to make decisions in conditions of uncertainty;
3. Applicability to objective functions with intersecting, derivative-indeterminate points;
4. Not using differential equations;
5. Being not stuck in the local extremum;
6. Applicability to processes with limited and uncertain information;
7. Facilitation of data processing by microcontrollers;
8. Adaptability and autonomy ;
9. Being able to reach the optimal solution in a short period of time.

In Chapter 2, the information-measurement and control systems of direct current microgrids, as well as automatic measurement, control and diagnostic structural-functional models, the mathematical model of circulating currents occurring in DC microgrids were developed, the effect of noise on measurement signals was minimized by digital filters. In order to build an intelligent control system in microgrids, it is necessary to develop a structural-functional model of the relevant information-measurement and control system. The information-measurement system of microgrids includes automatic measurement and control, technical-diagnostic, output power forecasting systems. In DC microgrids, it is necessary to measure the output voltage and current values of the converters and modules in real time to solve the necessary issues such as the stability of the output voltage of the converters, the distribution of the output power, and obtaining the maximum power from the PV modules.

The entire control process in the dissertation work was carried out based on the structural model of the proposed information-measurement and control system of the given microgrid. Figure 3 shows the structural model of the proposed information-measurement and control system.

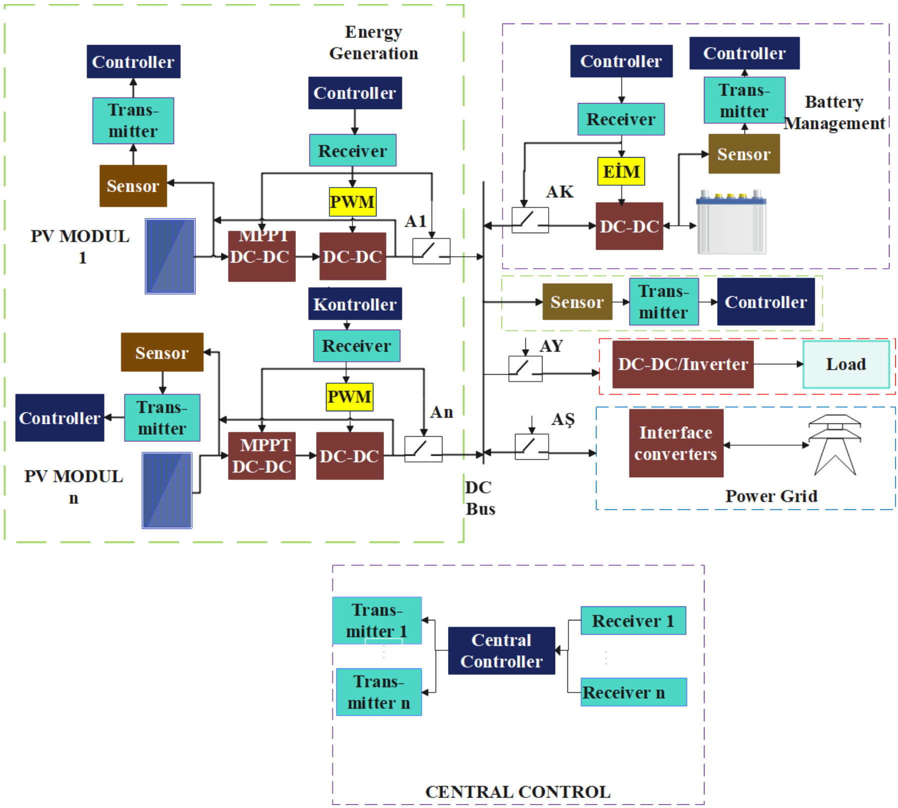

Figure 3. Structural model of the information-measurement and control system for photovoltaic microgrids

Various measurement-control, diagnostic and forecasting operations are performed here. The parameters of PV modules, converters and batteries such as voltage, current and temperature are measured in real time by means of transmitters. The obtained measurement results are transmitted to the central controller by means of transmitters. After processing these data in the central controller, the corresponding control signals are generated and transmitted. Measurements obtained from transmitters and transmission of control signals from the controller can be carried out in both wired and wireless environments. Control signals are obtained by means of receivers, and corresponding pulses are generated in the pulse width modulator (PWM) and fed to the transistors of the converters. When the measurement-control and diagnostic systems of the microgrid detect serious faults in the converters, the central control system of the microgrid immediately disconnects the respective converter from the bus by means of controlled switches (AK, AY, AŞ, A1..An) and maintains the stability of the bus voltage.

In order to improve the quality of the control process, it is necessary to denoise measurement signals. Figure 4 shows real-time values of the measurement signal affected by noise transmitted to the computer by the STM32F4 microcontroller.

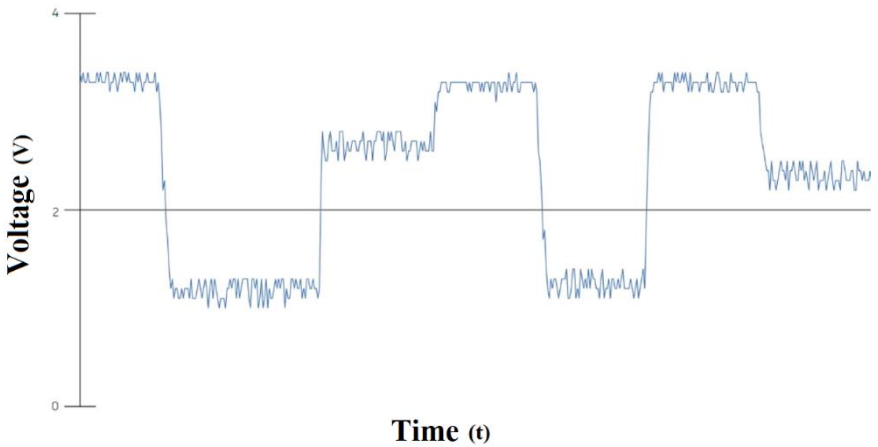

Figure 4. Measurement signal affected by noise

In this work, the digital filtering method based on finding the average value of the signal was used to clean the measurement signals from high-frequency noises. The real-time measured output voltages of the converters were transmitted to the microcontroller. The measurement signals are adapted to the 0-3.3V voltages of the microcontroller. As can be seen from the result, high-frequency noises were observed in the obtained measurement signals. These noises are significantly reduced at the software level by means of Figure 5, the real-time values of the noise level minimized measurement signal are reflected to the computer by the STM32F4 microcontroller.

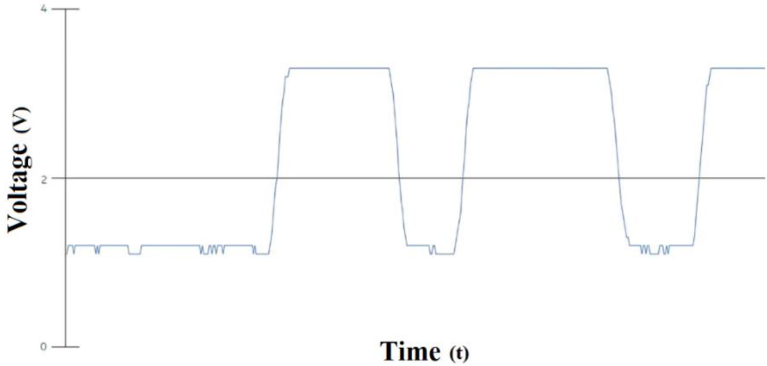

Figure 5. Measurement signal with minimized noise

Figure 6 shows two DC-DC converters connecting PV modules to a constant-voltage load circuit.

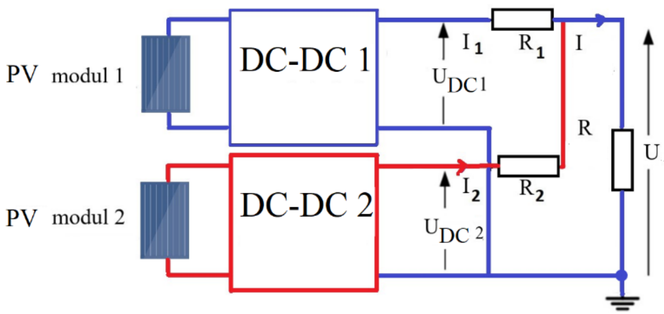

Figure 6. DC-DC converters with different output voltages connected to a single bus in parallel structure

When connecting multiple DC-DC converters in parallel in DC microgrids, the main points to pay attention to are the adjustment of the output voltages of the converters, the minimization of the power distribution differences between them, and the presence of circulating current. If the value of the output voltages of the converters connected to the same voltage bus in the parallel structure are equal, the output currents of the converters can be distributed equally. The physical phenomenon of circulating currents occurs at unequal values of the output voltages of the converters. From the obtained mathematical expressions, it is known that the current distribution difference depends on the output voltage of each converter and the parasitic resistance of the wire. The mathematical analysis of the circulating current for the two-converter system based on Kirchhoff's laws is carried out below :

$$I_{12} = -I_{21} = \frac{U_{DC1} - U_{DC2}}{R_1 + R_2} = \frac{I_1 R_1 - I_2 R_2}{R_1 + R_2}\,. \qquad (5)$$

Here, U_{DC1}, U_{DC2}, $R_1$and $R_2$the output voltages of the first and second converter and the parasitic resistances of the wire, respectively, $I_1$and $I_2$are the output currents of the first and second converters, respectively, $I_{12}$and is the circulating current directed from the first converter to the second converter.

When the number of converters is more than one, the formulas established above are summarized by the following expression:

$$\begin{bmatrix} I_1 \\ \cdot \\ \cdot \\ I_j \end{bmatrix} = \begin{bmatrix} \sum_{m\neq 1}^{n}\left(\frac{1}{R_1+R_m}\right) & \left(\frac{-1}{R_1+R_m}\right) \\ \cdot & \cdot \\ \cdot & \cdot \\ \left(\frac{-1}{R_n+R_1}\right) & \cdots \sum_{m\neq n}^{n-1}\left(\frac{1}{R_1+R_m}\right) \end{bmatrix} \begin{bmatrix} U_{SC1} \\ \cdot \\ \cdot \\ U_{SCj} \end{bmatrix}, \qquad (6)$$

$$j = 1, 2, \ldots n.$$

Figure 7shows n number of converters connected in parallel for constant voltage load resistance .

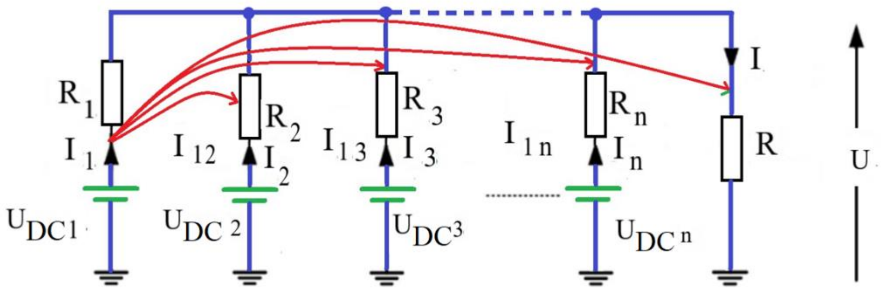

Figure 7. Equivalent electrical circuit of *n* number of DC-DC converters with different output voltages connected to a single bus

In Chapter 3, the generalized functional model of the intelligent control system of DC microgrids with metaheuristic MOTH-FLAME optimization (MFO) method, with the intelligent metaheuristic MOTH-FLAME algorithm was developed; the problems of minimizing the standard deviation of the output currents and bus voltage errors of the converters was solved; the maximum output power extraction from PV modules has been achieved and the design of the intelligent PID controllers was performed.

It is of particular importance to solve the tuning issues of multiple PID controllers involved in all three levels of the microgrid control system. It was determined that PID controllers with static parameter values do not have desirable dynamic and static characteristics in nonlinear, complex and dynamic processes present in DC converters. Under such conditions, the MFO algorithm was chosen to improve the characteristics of PID controllers. The MFO optimization method, included in the group of metaheuristic algorithms, is distinguished by a high speed of convergence to the optimal solution compared to other methods[1]. The improved characteristics of the PID controller with the MFO algorithm have

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[1]Elvin Yusubov, Lala Bekirova, A Moth-Flame Optimized Robust PID controller for a SEPIC in Photovoltaic Applications, IFAC-PapersOnLine,Volume 55, Issue

achieved high efficiency in real-time control of dynamic, complex processes by having adaptive tuning parameters. First, a matrix of random potential solutions was constructed to solve the PID controller optimization problems posed in the dissertation with $\boldsymbol{M_{PİD}}$ the MFO algorithm. Potential solutions are a set of proposed solutions for solving a given problem. The values of the proportional, integral and differential tuning parameters generated by the MFO controller were stored in the established potential solution matrix. A three-dimensional matrix of potential solutions was selected for each of the tuning parameters:

$$\boldsymbol{M_{PİD}} = \begin{bmatrix} m(p)_{1,1} & m(i)_{1,2} & m(d)_{1,3} \\ m(p)_{2,1} & m(i)_{2,2} & m(d)_{2,3} \\ \vdots & \vdots & \vdots \\ m(p)_{n,1} & m(i)_{n,2} & m(d)_{n,3} \end{bmatrix}. \tag{7}$$

Here *n* is the number of potential solutions. The number of columns is the number of variables (the size of the system).

A one-dimensional potential solution matrix was used for the optimization of the virtual resistance method solving power distribution problems with the MOTH-FLAME algorithm and for the maximum output power tracking controller:

$$\boldsymbol{M_{VR,MPPT}} = \begin{bmatrix} m_{1,1} \\ m_{2,1} \\ \vdots \\ m_{3,1} \end{bmatrix}. \tag{8}$$

The generation of the initial set of potential solutions is carried out according to the following function [2]:

$$\boldsymbol{M_{i,j}} = (\boldsymbol{ub}(i) - \boldsymbol{lb}(j)) * rand() + \boldsymbol{lb}\,(i). \tag{9}$$

[2]Mirjalili S. Moth-flame optimization algorithm: A novel nature-inspired heuristic paradigm. Knowl Based Syst, 2015 Nov; 89:228–49. Available from: https://doi.org/10.1016/j.knosys.2015.07.006

Here, the lower and upper limits are defined, respectively ***lb*** and ***ub*** vectors were used.

OM matrix is constructed to store the value of the objective function:

$$\boldsymbol{OM}_{\boldsymbol{P}\text{İ}\boldsymbol{D},\boldsymbol{VR},\boldsymbol{MPPT}} = \begin{bmatrix} OM_1 \\ OM_2 \\ \vdots \\ OM_n \end{bmatrix} \quad . (10)$$

Here n is the number of potential solutions.

In a similar manner, the matrix of feasible solutions ***F*** is constructed. It should be noted that both potential and feasible solution matrices are solutions. Feasible solutions are vectors of the most suitable solutions for a given optimization problem, selected from among potential solutions. The traditional spiral function was chosen as the main update mechanism [3]:

$$\boldsymbol{S}\,(\boldsymbol{M_i}, \boldsymbol{F_j}) = \left|\boldsymbol{F_j} - \boldsymbol{M_i}\right| e^{bk} \cos(2\pi k) + \boldsymbol{F_j}. \quad (11)$$

Here, $\boldsymbol{M_i}$- i - th potential solution, $\boldsymbol{F_j}$- j - th feasible solution, and S describes the spiral function ; b is the coefficient determining the shape of the spiral, and k is a random number chosen in the interval (-1, 1).

In order to evaluate the dynamic and static characteristics of the developed MFO-PID controller, relevant computer simulations were performed in the "MATLAB/SIMULINK" environment and a physical model was developed. The simulations were performed in two stages. In the first step, the developed MFO-PID controller's reference voltage tracking capability was implemented within the variations of the input voltage, simulating the variations of the output voltage of the PV module depending on the temperature and solar radiation intensity. In the second stage, the tracking ability of the support voltage at different values of the load resistance was tested.

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[3]Shehab, M., Abualigah, L., Al Hamad, H. et al. Moth-flame optimization algorithm: variants and applications. Neural Comput & Appl 32, 9859–9884 (2020). https://doi.org/10.1007/s00521-019-04570-6

Figure 8 shows the structural-functional scheme of the hierarchical control system of DC microgrids with PID controller improved by MFO algorithm.

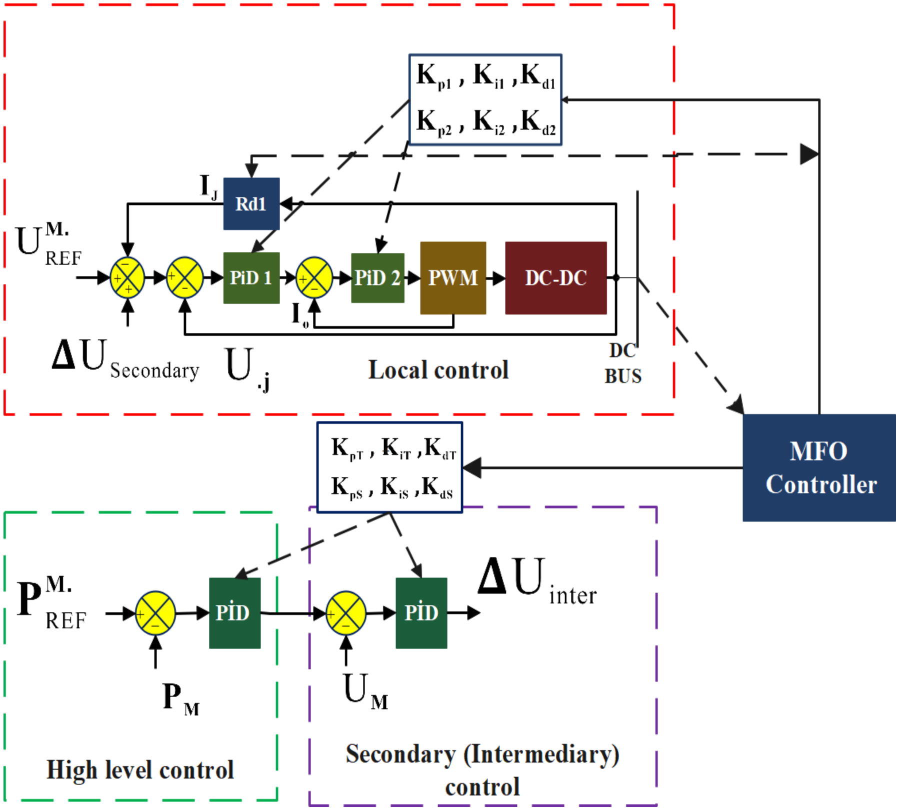


Figure 8. Hierarchical control system model of DC microgrids with PID controller optimized by MFO algorithm

As can be seen from the developed model, it is possible to adapt the tuning parameters of multiple PID controllers located at all three levels of control by means of the MFO algorithm. There are 1 PID controllers at the tertiary level and secondary levels of control, and up to 2 PID controllers at the local levels according to each inverter.

Figure 9 shows the tracking characteristics of the PID regulators tuned by the MFO and traditional Ziegler-Nichols methods, with input voltage from 10V to 14V at 1Hz frequency and under the influence of 7Ω load resistance.

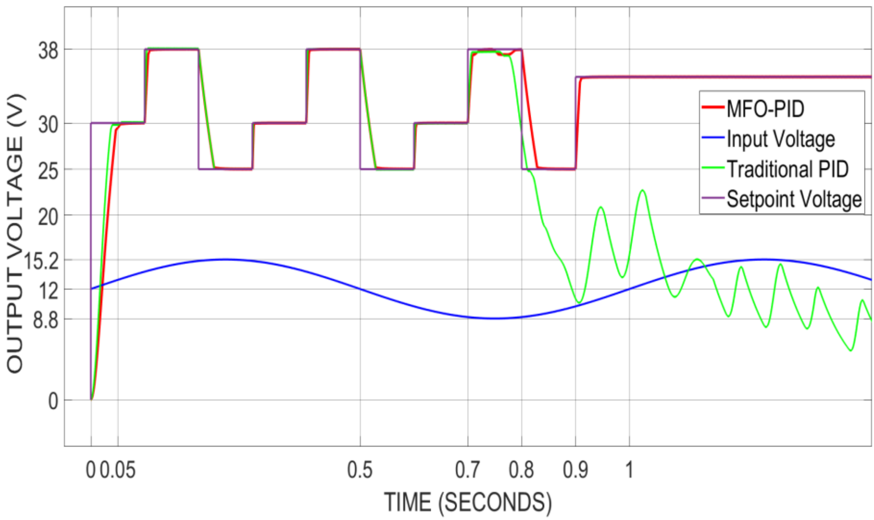


Figure 9. Dynamic response at 4V input voltage variation

As can be seen from the simulation results, both the optimized MFO-PID and the conventionally tuned PID regulators were able to successfully track the reference voltage at 10-14V periodic variations of the input voltage. Note that these input voltage variations mimic the output voltage variations of solar modules.

In Figure 10, a similar test was performed at varying input voltage values from 8.8V to 15.2V. Although the MFO-PID controller successfully tracks the changing values of the reference voltage, the PID controller tuned by the traditional method could not follow the reference voltage value at a given time starting from 0.8 second and lost its stability.

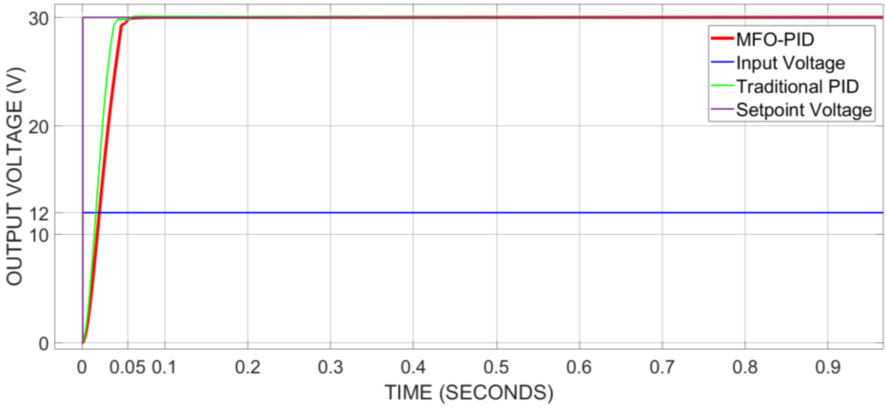


Figure 10. Dynamic process at 6.4V input voltage variation

Figure 11 and Figure 12 show the switching characteristics of both regulators when the load resistance changes from 7Ω to 5Ω when the input voltage is 12V and the reference voltage is 30V.

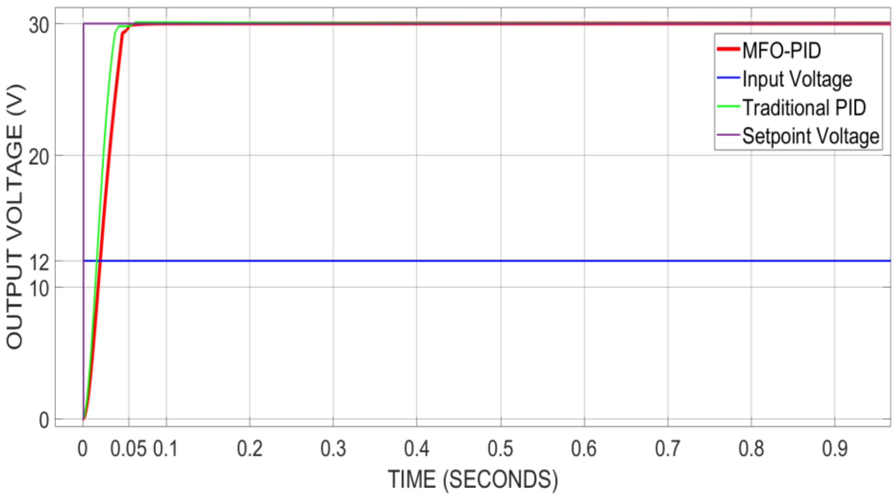


Figure 11. Dynamic characteristic at 7Ω value of load resistance

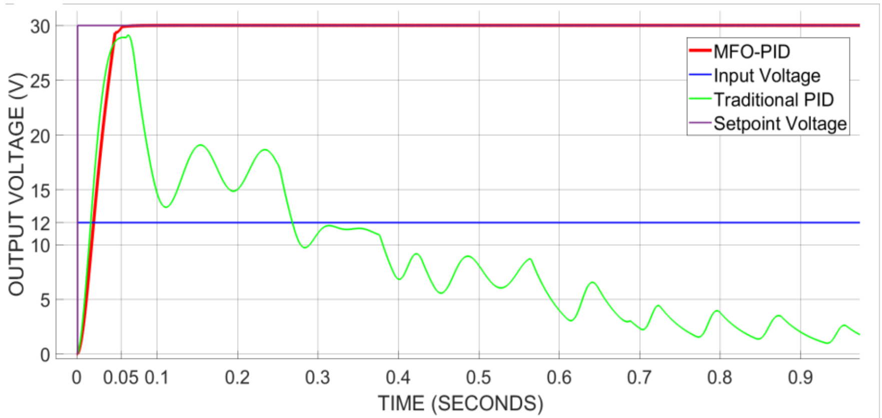
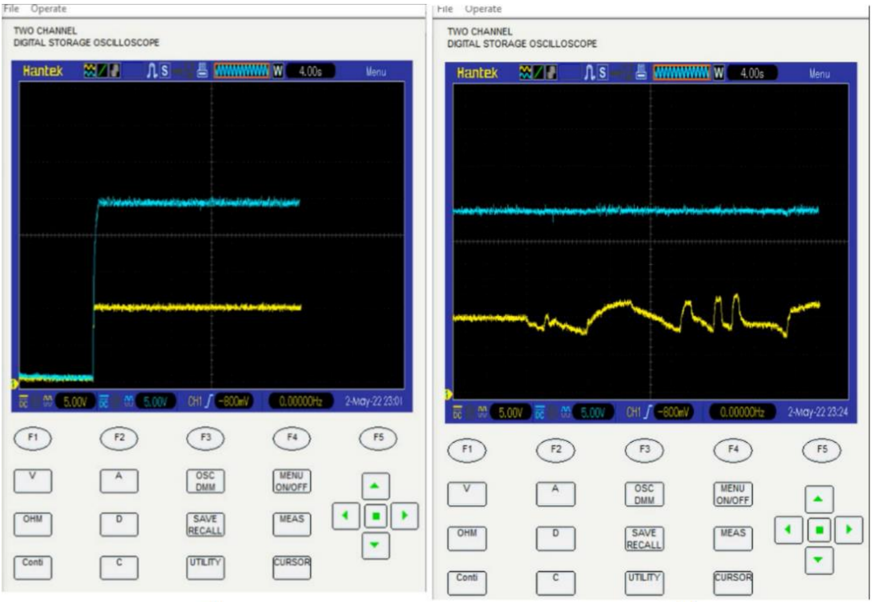


Figure 12. Dynamic characteristic at 5Ω value of load resistance

As can be seen from the simulation results, although both regulators have acceptable step response characteristics at 7Ω load resistance, when this resistance is reduced to 5Ω, the classical linear PID regulator has demonstrated unstable characteristics by not being able to follow the desired reference voltage. The selected STM32F407ZE microcontroller module was chosen to build the physical model of DC microgrids with improved PID controller.

Figure 13(a) shows the step response characteristics (25V reference voltage) of the physical MFO-PID controller. The data was obtained from the "HANTEK DSO5202P" real oscilloscope connected to the input and output of the converter and transferred to the computer. A 12 volt single impulse signal is applied to the input of the DC-DC converter and the reference signal at the output is 25V, successfully tracked with 0.05% accuracy. Note that the yellow color here corresponds to the input signal, and the blue color signal corresponds to the regulated output voltage.

In Figure 13(b), the input of the converter is given random voltage variations around 12V, and the stability of the reference signal at the output is maintained at 25V, 0.065% accuracy. In both switching and input voltage variations tests, the tuning parameters of the PID controller were changed adaptively.



a) b)

Figure 13. MFO-PID of the physical model of the regulator a) dynamic characteristics (25 V step response) , b) input voltage in variation static output characteristics

In order to minimize the differences in output power distribution between DC-DC converters at the local level, the method of virtual resistances is selected and optimized. This method is based on connecting non-physical virtual resistors to the output of each converter to increase /decrease the output current and power of the converters. By changing the values of virtual resistances, it is possible to adjust the values of the output power and current of the converters. In the traditional method of virtual resistances, the value of virtual resistances is static, determined individually for each converter connected to the bus in a parallel structure in advance, and cannot be changed adaptively in real time. Therefore, it does not allow real-time dynamic distribution of power. In order to minimize power distribution differences between converters during dynamic processes, it was determined that virtual resistances need to be adjusted in real time.

The mathematical model of the controller based on two-converter virtual resistances is given below:

$$U_{j\ NEW\ REF} = U_{j\ REF} - I_j R_{VR\ j}, \tag{12}$$

$$\Delta U_{sc} = |U_{DC\ REF} - U_{DC}| \leq \Delta U_{DC\ max.} \tag{13}$$

Here, the adjustable reference voltages ($U_{1\ REF}$, and $U_{2\ REF}$), output currents (I_1 and I_2),virtual resistances (R_{VR1} and R_{VR2}),are denoted by ΔU_{DC}- the error of the output voltage, $\Delta U_{DC\ max}$ and the maximum value of the error of the output voltage.

The value of the virtual resistance for the permissible voltage limits is given by the following formula:

$$R_{VR\ j} = \frac{(U_{j\ REF} - U_{j\ NEW\ REF})max}{I_j} \tag{14}$$

In order to minimize the distribution differences between the output powers of DC-DC converters, a method based on virtual resistances (VR) method optimized with intelligent metaheuristic MOTH-FLAME algorithm was developed. The objective function developed for the MFO-VR method is based on the approximation of the standard deviation value of the output powers of the DC-DC converters to 0.

To perform optimization with MFO, an objective function needs to be constructed. The objective function is structured in two main stages. At the first stage, issues of minimizing the differences between the output currents were considered. Assume that there are *n* DC-DC converters with corresponding output currents $(I_1, I_2, I_3, \ldots, I_N)$. The main objective is to minimize standard deviation value of these output currents by MFO algorithm in order to reduce the difference between the output currents.

The first bound of the developed objective function is given below:

$$min\,\sigma_I = \sqrt{\frac{\sum(I_J-\bar{I})^2}{N}} = \sqrt{\frac{(I_1-\bar{I})^2+(I_2-\bar{I})^2+\cdots+(I_N-\bar{I})^2}{N}}. \quad (15)$$

Here, σ_I −the standard deviation of the output currents ; I_J − current output current of the $\bar{I}j$ *-th* converter*; -* n is the average value of the output currents of the converter.

However, reducing the output current differences leads to undesirable changes in the bus voltage. In order to maintain the balance between voltage and current variations, a new mathematical term is additionally added to compensate voltage errors. In the second stage, along with the minimization of the standard deviation of the output currents, the reduction of the difference between the current output voltages and the reference voltages of the converters was considered. The updated form of the developed objective function is given below:

$$min\,z = \sqrt{\frac{\sum\left(I_J-\bar{I}\right)^2}{N}} + \frac{1}{N}\sum\left|U_{out.ref.J} - U_{out.J}\right|. \quad (16)$$

Here, $\Delta U_{error\ j}$ − the bus voltage errors, $U_{out.ref.J}$ − the reference voltage, $U_{out.J}$ − the current output voltage of the converter j.

In the conducted tests, the standard deviation curves of the output currents of the converters controlled by the traditional and proposed MFO-PID method are given in a comparative form. Both converters are connected to the same bus. The reference voltages of the second converter were time-shifted in steps of $\pm$0.25 V to create an artificial difference in the output voltages of the converters .

Figure 14(b) shows the VR controller with static and adaptive parameters of standard deviation (STD) of the converter output currents. While the STD of the adaptive parameter VR controller with higher output performance approaches 0, the STD of the static coefficient VR controller is settled around 2. The output reference voltages of the converters Figure 14

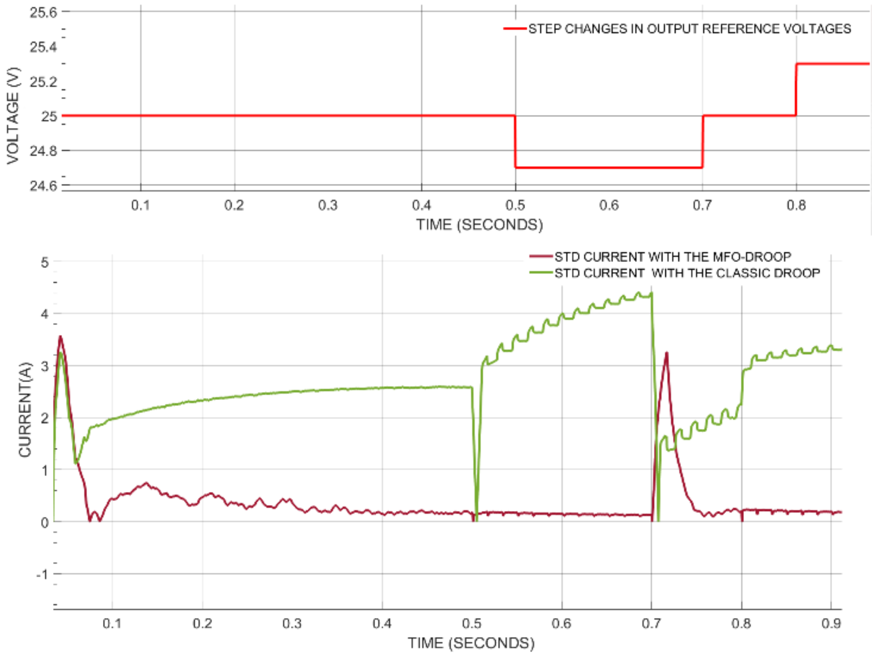


Figure 14. Standard deviation of output currents

Compared with the traditional VR control, the MFO-VM method achieved the minimization of the current distribution error. As can be seen from the results, the power distribution error with the proposed MFO-VR controller is very small compared to the power distribution error with the traditional VR controller. The numerical results of the simulation are given in table 1.

Table 1

Comparative simulation results of VR and MFO- VR controllers

Support voltages	**25 V**	**24.75 V**	**25.25 V**
STD of current	2.35/0.4	4/0.2	3.4/0.25
Average current difference (A)	3.4 /0.15	5.5/2	4.6/0.35
Average power difference (W)	80/6	140/7.8	110/8
Average voltage difference (V)	0.05/0.01	0.2/0.23	0.1/0.12

Figure 15 and Figure 16 show the differences between the output powers of conventional and MFO-VR controller converters.

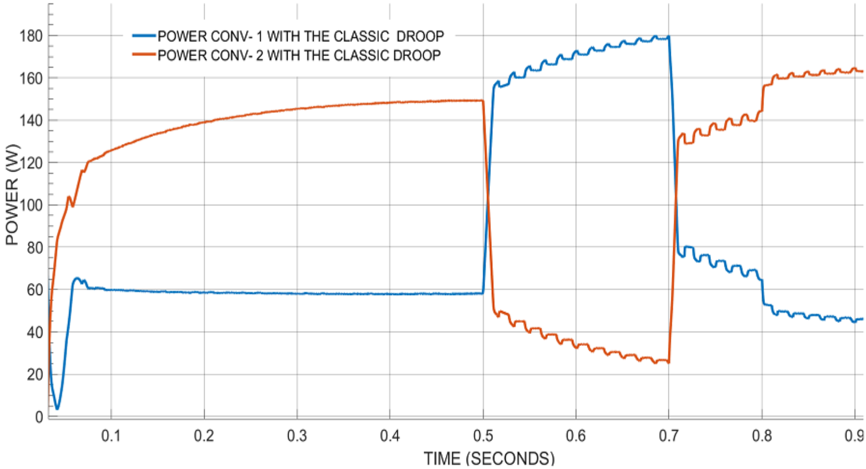


Figure 15. Output power of converters with traditional VR controllers

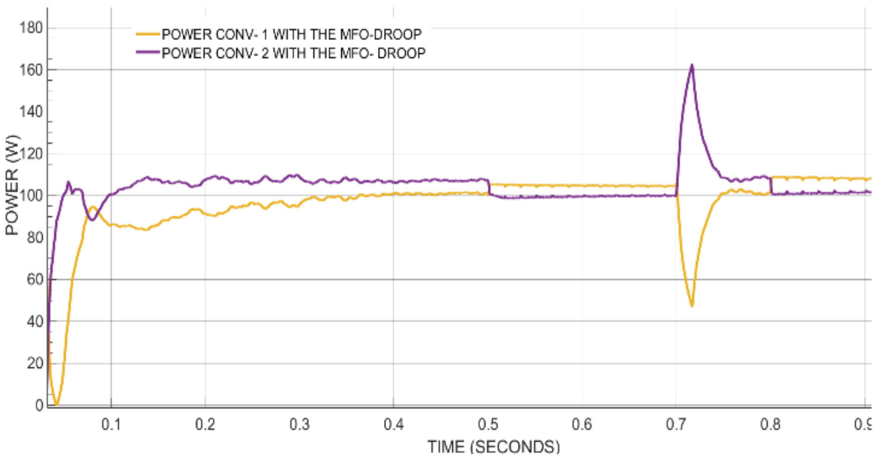


Figure 16. Output power of converters with the new MFO-VR controllers

In this chapter, the traditional maximum power point tracking (MPP) methods were also comparatively analyzed and the occurrence of multiple extremes in the output characteristics of PV modules under the influence of partial-shading physical phenomenon was observed. It has been established by experiments that traditional methods fail to find the global maximum in multi-extreme characteristics in many cases. Figure 17 shows the output power-voltage characteristic of the photovoltaic module.

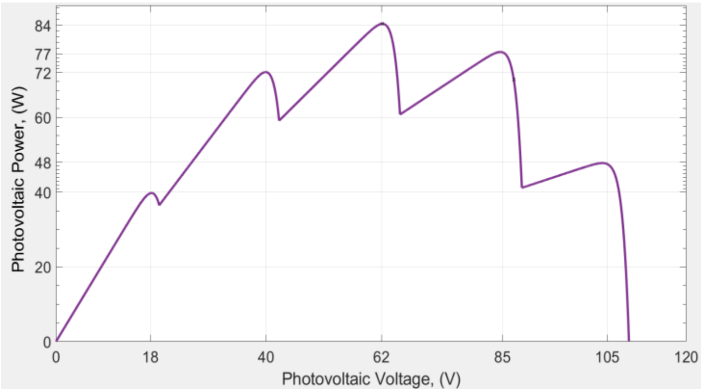


Figure 17. Output characteristics of PV modules in half-shading conditions

Taking into account that metaheuristic optimization methods are effective in finding the maximum point in multi-extremum functions, it is considered more appropriate to choose a metaheuristic algorithm for the given problem. To demonstrate the effectiveness of the developed MFO-MPPT method, PSO-MPPT controllers based on traditional pertubation and particle swarm intelligence were developed and simulations were carried out. All selected photovoltaic modules were identical and simulated under partial-shading conditions. The MPPT controller uses the MFO algorithm to determine the maximum power point by measuring the output voltage and current of the photovoltaic module. The controllers have been subjected to some tests to evaluate the ability to track the maximum point. As can be seen from the graph, the maximum power of 84 W is achieved at 62 V. Local maxima were observed as 40 W at 18V , 72 W at 40V, 77 W at 85V and 48 W at 105V.

Figure 18 shows the simulation results of photovoltaic output power monitored by all three controllers. Although the MFO and particle swarm intelligence (PSO) MPPT controllers can track the global maximum point of 84W, the PSO- MPPT algorithm gets stuck at the local maximum and obtains a value of 77W . Although the PSO and MFO-MPPT controllers were both able to detect the global maximum, the proposed MFO algorithm achieved it with a settling time of 0.6 seconds. In the PSO-MPPT controller, the settling time was 5 times longer, i.e. 3 seconds. The voltages at which the maximum power is observed are 62 V, 62 V and 85 V in the PSO, MFO and pertubation controller, respectively.

Figure 18. Output characteristics of MPPT controllers under half-shading conditions

The numerical values of the measurements are given in table 2, respectively.

Table 2

Comparative measurement results of ZSI, Pertubation and MFO- MGNI controllers

MPPT controllers	**Pertubation**	**PSO**	**MFO**
Monitored maximum power	61-77 W	84 W	84 W
Voltage	85 V	62 V	62 V
Convergence Speed	Down	Mediu m	Fast

One of the other important tasks of the central intelligent control system of the microgrid is to provide uninterrupted power supply to the load circuit. However, in some cases, the total output power of the PV modules may not be sufficient for uninterrupted power supply of the load circuit. The main purpose of batteries and the utility grid is to deliver the required power to the load circuit in such cases. Here $\sum_1^N P_{PV}$- the sum of the output power of the PV modules, $\sum_1^N P_{BAT.}$the sum of the output power of the batteries, $P_{GR.}$ - the grid power , $\sum_1^N P_{LD}$- the power required by the load circuits. Central controller, depending on the $\sum_1^N P_{PV}$ values of $\sum_1^N P_{BAT.}$, $P_{GR.}$, $\sum_1^N P_{LD}$, corresponding energy sources are connected to the load circuit. The logical state value of the connection is 1- indicates that the corresponding source is connected to the load circuit, and 0 indicates that the source is disconnected from the load circuit. Batteries are characterized by charging (+1 logical state), discharging (-1 logical state) and standby (0 logical state). By theoretically obtaining the upper and lower limits of state of charge of batteries in the control process, it is possible to prevent their overcharging and discharging issues. This also serves to increase the longevity of the batteries. The main advantage of the proposed algorithm is the ability to maintain the balance between the generated power and the required power. Figure 19 the proposed microgrid power flow control algorithm is described.

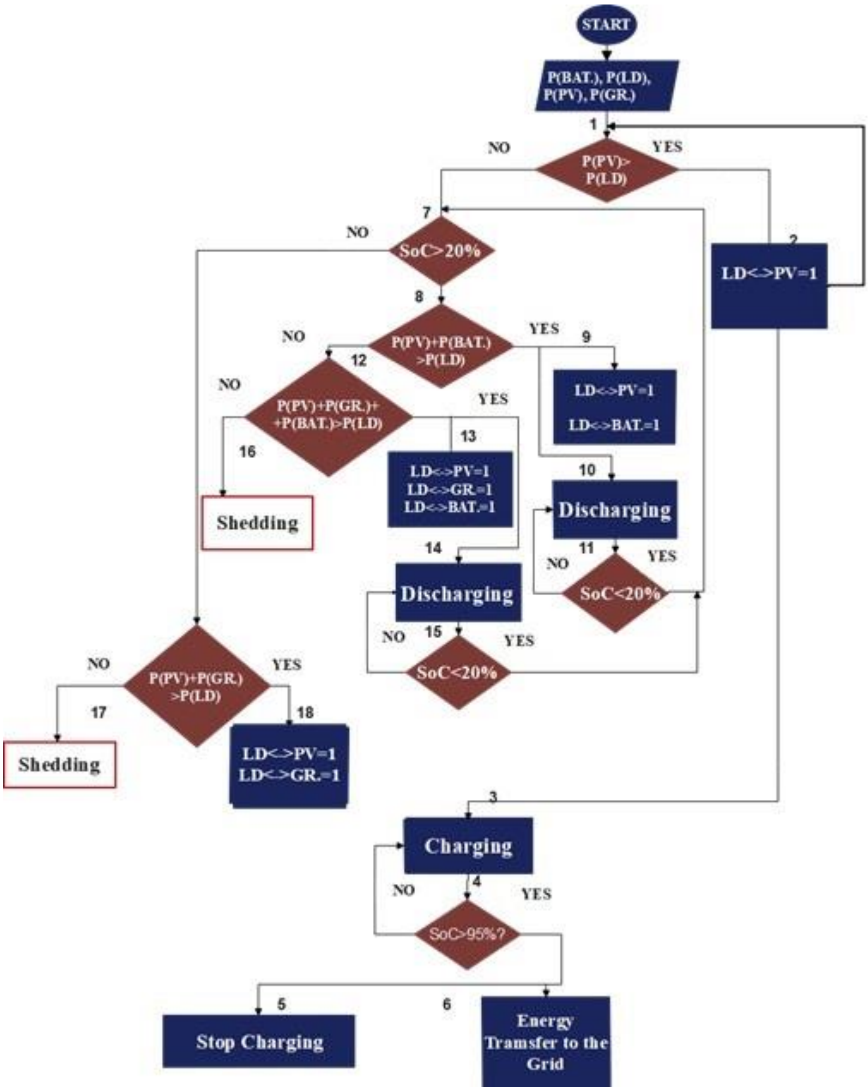


Figure 19. Proposed power flow control algorithm in DC microgrid

Another advantage of the model is the charging and discharging of batteries with a constant bus voltage, which is calculated to increase the stability of the DC bus voltage.

In Figure 20, the functional model of the proposed new intelligent measurement-control and control system of DC microgrids is described.

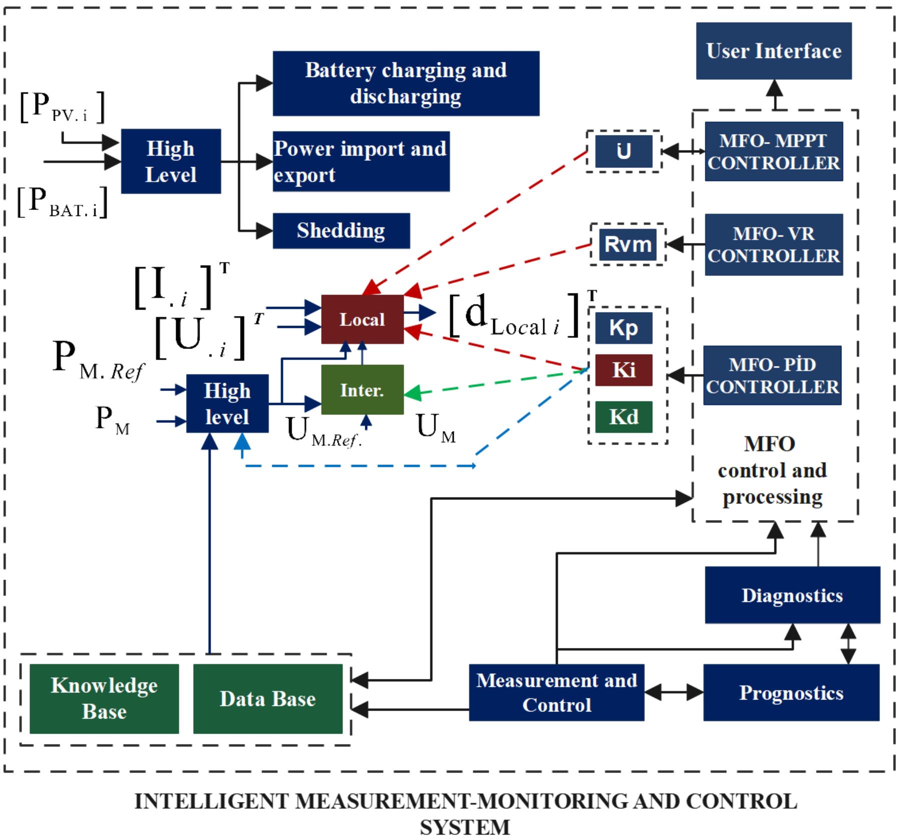


Figure 20. A new functional model of the intelligent measurement-control and control system of DC microgrids

A new functional model of the intelligent measurement-control and control system of direct current microgrids was developed in the thesis work. The generalized functional model includes the following main functional blocks:

1) MFO-PID regulators,
2) MFO-VR controller,
3) MFO-MPPT controller,
4) Forecasting,
5) Automatic-measurement and control,
6) Diagnostics,
7) Database and knowledge base.
8) Local, upper and intermediate levels of control.

Based on the value of the maximum power produced from the PV modules, the upper control level generates appropriate control signals for the lower levels. The main purpose of the automatic measurement and control system is to constantly measure the parameters of the microgrid, such as voltage, current, load amount, as well as the temperature of the PV modules and batteries, and control whether they are within the specified allowable interval.

THE MAIN RESULTS OF THE DISSERTATION WORK

The main scientific results obtained in the dissertation work are as follows:

1) In order to perform optimal control, the standard deviation minimization problem of output currents and bus voltage errors was solved with the intelligent metaheuristic MOTH-FLAME algorithm [5,6];
2) A new structural-functional model of intelligent information-measurement and control system for DC microgrids was developed [12];
3) For the development of the DC microgrid intelligent control system, the reasons for selecting converters with unidirectional SEPIC for connecting to photovoltaic modules and bidirectional SEPIK-ZETA converters for the interface with the battery are established, their corresponding state-space equations and transfer functions are derived [1,2,10,11] ;
4) A mathematical model of circulating currents in DC microgrids has been developed [5,6] ;
5) A comparative analysis of traditional and metaheuristic optimization methods was conducted and the reasons for selecting the metaheuristic MOTH-FLAME algorithm for developing the intelligent model of the microgrid control system were justified [3,4,5,6,8,14];
6) The development issues of intelligent PID controllers at all three control levels of the microgrid have been solved [1,2,3,4];
7) A physical model of the intelligent PID regulator with improved characteristics was realized based on the "STM32F407" microcontroller [1,2, 4] ;
8) A new method for tracking the maximum power point with the metaheuristic MOTH-FLAME algorithm, which allows extracting the maximum output power based on the measurement results of the output parameters of photovoltaic modules, has been developed [5,7];

9) A generalized functional model of the intelligent control system of microgrids has been developed [4,5,7];
10) A new functional model of the intelligent control system, which has the ability to carry out optimal energy exchange with other microgrids or the utility grid, has been developed for the uninterrupted supply of load circuits in DC microgrids with the internal functional blocks of the microgrid [9,10,12, 13,15].

Publication on the topic of the dissertation work list of published scientific works

1. Yusubov E. and Bakirova L., «A Self-Tuning Fuzzy PID Controller for SEPIC Based on Takagi-Sugeno Inference System,» International Conference Automatics and Informatics (ICAI), 2021, pp. 54-57, doi: 10.1109/ICAI52893.2021.9639804.
2. Yusubov E. and Bakirova L. " Design and Simulation of the Auto-Tuning TS-Fuzzy PID Controller for the DC-DC ZETA Converter, " International Scientific and Practical Conference «Intellectual Systems and Information Technologies», September 13–19, 2021, Odesa, Ukraine ISSN- 1613-0073. http://ceur-ws.org/Vol-3126/paper36.pdf
3. Yusubov E. and Bakirova L., A Moth-Flame Optimized Robust PID controller for a SEPIC in Photovoltaic Applications, IFAC-PapersOnLine,Volume 55, Issue 11, 2022, Pages 120-125, ISSN 2405-8963, https://doi .org/10.1016/j.ifacol.2022.08.059 .
4. Yusubov E. and Bakirova L., Development of an improved hierarchical control system using the metaheuristic PID tuner for DC microgrids. Advanced Information Systems, 6(3), 42–47, 2022, ISSN-2522-9052, https://doi.org/10.20998/2522-9052.2022.3.06
5. Yusubov E. and Bakirova L. , «A Robust Metaheuristic Central Controller for the Hierarchical Control System with the Adaptive Power sharing and MPPT in DC Microgrids'

International Journal on Technical and Physical Problems of Engineering (IJTPE) Journal, Issue 53, Vol. 14, No. 4, December 2022. https://www.iotpe.com/IJTPE/IJTPE-2022/IJTPE-Issue53-Vol14-No4-Dec2022/54-IJTPE-Issue53-Vol14-No4-Dec2022-pp392-399.pdf

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12. Yusubov, E., Design of an intelligent information measurement system for photovoltaic dc microgrids. Proceedings of Azerbaijan High Technical Educational Institutions, ASO I U, Volume 34, Issue 11, pp 54-64, 2023. https://zenodo.org/records/10062961
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15. Yusubov, E., Bakirova L., A Standalone DC Microgrid Energy Control Strategy Using The Battery State Of Charge. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska, Poland, 3/2023, pp 75-78 . http://doi.org/10.35784/iapgos.5320 .

Personal activity of the candidate in cases with co-authors:

[1-4,14]- Control issues in complex, non-linear processes, investigation of characteristics of PID controllers in non-linear systems, development of state equations and transfer functions of converters, conducting simulations, optimization of PID controllers with metaheuristic MOTH-FLAME algorithm ;
[6]- Development and computer simulation of the objective function based on iterative reduction of the standard deviation error for the meta-heuristic central controller at the local control level of the microgrid ;

[7]- Development of maximum power tracking controls of power converters in partial-shading conditions with meta-heuristic MOTH-FLAME optimization method;
[9, 10, 13, 15]- Development of a new functional model for maintaining the balance of power required and generated in the microgrid;
[4, 5]- Metaheuristic optimization of the hierarchical control system of the DC microgrid, computer simulations, development of a new structural-functional model, determination of working modes of the microgrid's energy storage and control system;

The defense will be held on the March 29th, 2024 at 11:00 at the meeting of the Dissertation Council ED 2.04 of Supreme Attestation Commission operating under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University.

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