POWER MACHINERY

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MAXIMUM POWER POINT TRACKING FOR PHOTO MODULES

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Abstract—*It is considered the problem of maximum power point tracking for photovoltaic modules. The solution of this problem is based on a static parametric meta-optimization for swarm intelligence algorithms. For the problem solution Particle Swarm Optimization algorithm meta-optimized with Bat Search algorithm is proposed. The basic idea for the algorithms is that they consist of the base algorithm, which is used to solve the main optimization problem and the meta-algorithm used to find an optimal strategy for the base one. The object function for the base algorithm is an object function of the general optimization problem. The meta-algorithm evaluates the meta-function defined at each generation and tries to minimize it by searching for better strategies for the base algorithm. It is considered the example of its application.*

Index Terms—Maximum power point tracking; photo-voltaic modules; renewable energy sources; meta-algorithm; swarm intelligence algorithms; Bat Search algorithm; Particle Swarm Optimization.

I. INTRODUCTION

Renewable energy is energy produced by a resource that quickly fills (recovers) as a result of a natural or nonstop natural process.

From an economic point of view, renewable energy sources (RES) can be considered as an effective means of stimulating innovation and business activity in national economies, creating additional jobs, creating new significant sources of income from equipment import.

According to the International Energy Agency (IEA) [1], electricity consumption in the world will reach 26 trillion kW/h by 2025. Additionally, the installed capacity of the power plants will reach 5500 GW. The corresponding parameters are also estimated to reach 32 trillion kW/h and 5900 GW by 2035. The heads of the leading states consider RES to play a significant part (about 44%) in achieving the stated parameters since the traditional methods of generating electricity with limited primary resources, cause some environmental damage [2].

It has been proved that increasing the volume of RES production and their share in the energy balances contributes to improving the efficiency of economic activities of different energy consumers and enhances trust between the countries that have included RES in the list of strategic priorities of their development.

In order to obtain the maximum possible power at the output of photomodules, electric generators of wind turbines, electric generators with variable rotation speed and torque, electric motors operating in regenerative braking mode, the maximum power point tracking (MPPT) method is used.

Most often, MPPT devices are used to optimize the maximum power of solar photovoltaic batteries (photo modules) when using solar energy. This is due to the fact that the illumination of photomodules during the day varies significantly from the position of the sun in the sky, cloudiness, precipitation, which causes a profound change in the load characteristic of photo modules. To obtain the maximum power point, it is necessary to change the current taken from the photo modules, while the voltage on the photovoltaic battery changes.

II. PROBLEM STATEMENT

The output power of any solar panel depends on many parameters. They can be divided into two main groups:

1) primary, which affect the current-voltage characteristic of solar cells, such as environmental

conditions, such as the level of solar radiation, the temperature of solar panels;

2) secondary, which directly affect the output power, such as the characteristics of the connected load.

For example, with an increase in the level of solar radiation, the output power and current of the solar panels will increase linearly, but with a simultaneous increase in the temperature of the solar panels, the output will decrease.

Based on the fact that solar cells have a rather complex relationship between environmental parameters and output power, we can say that the current-voltage characteristic also changes from these parameters, therefore, it can be represented as a certain curve that depends on specific instantaneous values of the environment. Also, on the current-voltage characteristic there is a specific point at which certain values of current and voltage, depending on the selected load (according to Ohm's law), will correspond to the point of maximum power, which is the global maximum on the power curve (power characteristic). The composition of the CVC and power characteristics, with the display of the maximum power point (MPP) is shown in Fig. 1.

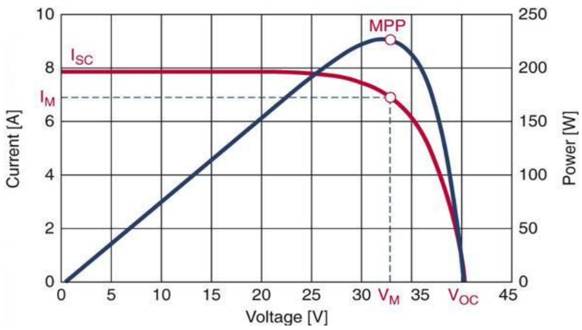

Fig. 1. Composition of I–V and P–V curves, with a maximum power point displayed on them

For the operation of solar panels at the point of maximum power or at the operating point, DC-DC converters are most often used, which are placed between the solar panels and the load (consumers), These DC-DC converters are controlled by an additional unit that provides the implementation of the algorithm for finding the maximum power point.

The main feature of the DC-DC converter with MPPT is that it is a full-fledged electronic system that performs power increase using certain approaches to controlling the converter.

The maximum power of the panel at the operating point can be represented as power at the points U_{mpp} and I_{mpp}, which are located on the I–V curve:

$$P_{\max} = I_{mpp} U_{mpp}. \quad (1)$$

where U_{mpp}, I_{mpp} is the voltage and current at the maximum power point, respectively.

Since the power maximum is one extreme of the power curve, then it satisfies the following condition (by Fermat's theorem):

$$\frac{dP}{dU} = 0. \quad (2)$$

Due to the fact that MPP can move on the power curve at different moments in time and system operation, due to the dependence on temperature and irradiance level, for its search in real time, MPPT algorithms should be applied, which will be discussed later in this paper.

The effectiveness of solar panels also directly depends on the operating mode, and in MPP it will be the maximum possible for a particular instance of panels:

$$\eta = \frac{I_{mpp} U_{mpp}}{P_S} = \mathrm{FF} \frac{U_{OC} I_{SC}}{\int_0^\infty P(\lambda) d\lambda}, \quad (3)$$

where $P(\lambda)$ is solar radiation depending on the wavelength of solar photons; P_s is solar power; U_{OC} is the voltage on the solar panel in open circuit state; I_{SC} is the panel current in short circuit state; FF is the occupancy factor, which is defined as:

$$\mathrm{FF} = \frac{I_{mpp} U_{mpp}}{U_{OC} I_{SC}}. \quad (4)$$

When it comes to harvesting solar energy in large scales, the PV modules are arranged and connected in series and parallel combinations to produce the desired voltages and currents. Conventional MPPT techniques perform well with uniform solar irradiance. However, shades from different objects (e.g. buildings, trees), clouds etc. cause variable irradiance of the modules, which leads to partial shading phenomena. When partial shading condition occurs, the output power of some modules will decrease dramatically and result in unbalanced conditions in the whole system. Due to intrinsic characteristics of photovoltaic cells, shadows can dramatically decrease the module's output current. To avoid this phenomenon and its such harmful effects like creating hotspots, bypass diodes are utilized [3]. In partial shading conditions, the PV system's power on the voltage curve characteristics will experience several peaks, thus the ability of the conventional techniques to track the accurate MPP is not guaranteed.

When developing a search method, it is necessary to solve the following problems:

- improvement of the search speed;
- adaptability to dimming conditions;
- reducing the cost of the system;
- correction of defects in conventional search algorithms.

Accordingly, it is possible to formulate the main criteria for search methods:

- complexity of the algorithms;
- the complexity of the implementation of the algorithm is applicable to solar energetic system;
- global maximum power point search speed;
- accuracy and search efficiency.

III. STATIC PARAMETRIC META-OPTIMIZATION FOR SWARM INTELLIGENCE ALGORITHMS

Let's call the vector of behavioral parameters of the swarm algorithm *a strategy of the algorithm*. The strategy determines the effectiveness of the algorithm. There are several ways one can obtain the rational set of parameters for a specific algorithm to solve a specific task. One way is to determine strategy by hand-tuning, but as the number of parameters increases, the number of possible combinations of parameters' values grows exponentially, and evaluating all of such combinations becomes a very hard computational task. That's way we need another approach for searching for the best strategy. The one which is covered in the article is called meta-optimization and it is implemented with additional layer of optimization. Basically, one algorithm's parameters are tuned by another algorithm. One type of such optimization problem is called parameter adaptation problem.

A. Parameter Adaptation Problem Statement

The first important step to solve the meta-optimization problem is to formulate it using mathematical notation.

The parameter adaptation problem implies that the optimal strategy for the tuned algorithm is static and is searched for a specific optimization problem.

Let function $f(X)$ be an optimization problem, which maps vector of parameters X to a fitness measure:

$$f:\mathbb{R}^n \to \mathbb{R},$$

where n is the dimension of vector X.

The optimization problem itself is formulated as finding the optimal solution $X^{\min}$, which satisfies the equation:

$$\forall Y \in \mathbb{R}^n : f(X^{\min}) \le f(Y).$$

Let $a(B)$ be a base algorithm used to solve the aforementioned optimization problem, where $B=\left(b_1, b_2, ..., b_{|B|}\right)$ is the strategy of the base algorithm. Let's also define the upper and lower bounds b_i^{lower}, b_i^{upper} for each element of the B. The bounds are specific to the optimization problem. Than D_B is a set of possible strategies of the algorithm $a(B)$:

$$D_B = \left\{ b_i \left| b_i^{lower} \le b_i \le b_i^{upper},\ i \in \left[1:|B|\right] \right.\right\}.$$

The meta-optimization (parameter adaptation) problem is formulated as finding such strategy $B^{best} \in D_B$ of the algorithm $a(B)$ for a problem $f(X)$, which minimizes the object meta-function $\mu(f, B)$:

$$\min_{B\in D_B} = \mu\left(f, B\right) = \mu\left(f, B^{best}\right).$$

B. Meta-function Variants for Parameter Adaptation Problem

In this paper, it is proposed to use the following performance and efficiency meta-functions for the meta-optimization problem. The first suggested meta-function:

$$\mu_1\left(f, B\right) = score\left(B\right),$$

where $score(B)$ is the value of the objective function at the solution provided by $a(B)$.

The second suggested meta-function:

$$\mu_2\left(f, B\right) = evals\left(B\right),$$

where $evals(B)$ is the number of objective function evaluations for the whole optimization process with algorithm a using strategy B. Note that this meta-function should be used when the termination criterion is not just surpassing some maximum number of iterations, but when we also specify some tolerance to be reached. One way to check if the satisfactory tolerance is achieved is to use a stagnation criterion.

The meta-function, which will be used in meta-optimization process, is represented by the additive convolution of the above ones:

$$\mu\left(f, B\right) = \lambda_1\mu_1\left(f, B\right) + \lambda_2\mu_2\left(f, B\right),$$

where $\lambda_{1,2}$ *are* weight coefficients for each estimation.

C. Description of the Swarm Intelligence Algorithms with Meta-optimization

The basic idea for the algorithms is that they consist of the base algorithm, which is used to solve the main optimization problem and the meta-algorithm used to find an optimal strategy for the base one [4]. The object function for the base algorithm is an object function of the general optimization problem. The meta-algorithm evaluates the meta-function defined at each generation and tries to minimize it by searching for better strategies for the base algorithm. It may be a good practice to set some parameters of the base algorithm before the meta-optimization process, so that the search space for the meta-algorithm is smaller, thus the computational time is shorter. The strategy for the meta-algorithm is set manually.

D. Meta-optimization and Base Algorithm Choice

One of the main problems of parameter adaptation problem is to choose the appropriate meta and base algorithms. The optimization for the above meta-function requires a lot of calculations, as we basically do a full optimization process at each generation of the meta-algorithm. So, it is desired to achieve the satisfactory result in the least possible amount of time by using proper meta and base algorithms. The way we make a choice among other available algorithms is based on several criteria. The suggested criteria for the base algorithm choice.

1. Has the best average score among all of the other available algorithms at some specified amount of iterations $T_{\max}$ on a set of test functions for optimization.
2. Has the shortest evaluation time for the $T_{\max}$ iterations on a number of test functions for optimization.
3. Has a small number of parameters to optimize over. The less dimensions the search space has, the faster is the optimization process.

The suggested criteria for the meta-algorithm are formulated as follows.

1. Obviously, the meta-algorithm has to improve the best average score of the base algorithm at some specified amount of iterations $T_{\max}$ on a set of test functions for optimization.
2. Has the shortest evaluation time for the $T_{\max}$ iterations on a number of test functions for optimization.

E. Meta-algorithms Parameters' Initialization

Another problem of meta-optimization is to properly set the meta-algorithm's population size and parameters (strategy). So, here are some recommendations how to do it.

Increasing the population size may improve the meta-optimization solutions, but it also makes the computations more complex. The population is chosen based on the dimension of the base algorithm strategy search space. For instance, for the Particle Swarm Optimization (PSO) algorithm as a meta-algorithm and search space dimension D = 2 the population size may vary from 10 to 20; for D = 3 we may want to increase the number of particles, so that the size is about 20 to 30.

As for the strategies, the choice is based on the bounds of the base algorithm strategy search space. All of the swarm intelligence algorithms have parameters, which control the particles step and exploration/exploitation rate. So, for search spaces with small ranges of parameters, we may want to set the step size to be relatively small.

Particle Swarm Optimization meta-optimized with Bat Search.

Base algorithm: PSO.

Meta-algorithm: Bat Search.

The Particle Swarm Optimization algorithm was already described, so let's describe the Bat Search principles. The algorithm flow can be summarized as follows: each bat, which represents a solution, flies randomly in the search space with some velocity with a varying frequency or wavelength and loudness. As it searches for its prey, it changes frequency, loudness and pulse emission rate to control the way it moves. Search is intensified by a local random walk around the current global best solution. Selection of the best continues until certain stop criteria are met.

The algorithms is based on idealized model of bats' behavior. This model has the following rules:

- bats can distinguish prey from obstacles and sense the distance to them by the means of echolocation;
- bats fly randomly with velocity V_i at position X_i with a fixed frequency $f_{\min}$, varying wavelength λ and loudness A_0 to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission $r \in [0; 1]$, depending on the proximity of their target;
- although the loudness can vary in many ways, we assume that the loudness varies from a large (positive) A_0 to a minimum constant value $A_{\min}$.

Each bat is a potential solution to the problem. The coordinates of the bat i at iteration t are defined as a real-number D-dimensional vector $X_i^t = \left(x_{i,1}^t, x_{i,2}^t, ..., x_{i,D}^t\right)$. Each bat i moves in a search space with a velocity $V_i^t = \left(v_{i,1}^t, v_{i,2}^t, ..., v_{i,D}^t\right)$.

The update rule for the solutions and velocities:

$$f_i = f_{\min} + \left(f_{\max} + f_{\min}\right)\beta,$$

$$V_i^{t+1} = V_i^t + \left(X_i^t - X^{gbest}\right) f_i,$$
$$X_i^{t+1} = X_i^t + V_i^{t+1},$$

where β is a random vector drawn from a uniform distribution at the interval [0; 1]; X^{gbest} are coordinates' vector which corresponds to the best solution found globally by all bats for all of the iterations.

For the local search part, we generate a new solution using random walk:

$$X_{\text{new}} = X_{\text{old}} + \varepsilon \bar{A}^t, \quad \bar{A}^t = \frac{1}{N}\sum_{i=1}^{N} A_i^t,$$

where ε is the *D*-dimensional vector of uniformly distributed values at the interval [-1; 1]; $\bar{A}_i^t$ is the average loudness of all the bats at the iteration *t* as it may be assumed from its definition.

The loudness and the rate of pulse emission for each bat have to be updated accordingly as the iterations proceed. New values are given by

$$A_i^{t+1} = \alpha A_i^t, \; r_i^{t+1} = r_i^0\left[1 - \exp(-\gamma t)\right].$$

where α and γ are constants, so that for any 0 < α < 1 and γ > 0.

Base algorithm parameters (strategy): ω (inertial parameter), c_1, c_2 are acceleration parameters, which correspond to cognitive and social components of each particle.

Meta-algorithm parameters: minimal frequency $f_{\min}$, maximum frequency $f_{\max}$, initial loudness A_0, initial rate of pulse emission r_0, coefficients α and γ. The pseudo code for the PSO parameters adaptation with Bat Search:

begin
Meta-function μ(B)
Define the meta-algorithm's parameters
Generate initial population of N bats for the meta-algorithm
while *a termination criterion is not met* **do**
Generate new solutions by adjusting frequency
Update velocities and locations/solutions
if *(rand >r_i)* **then**
Select a solution among the best solutions
Generate a local solution around the selected best solution
end if
Generate a new solution by flying randomly
if *(rand <A_i&μ(B_i) <μ(B^{gbest}))* **then**
Accept the new solutions
Increase r_i and reduce A_i
end if
Rank the bats and find the current best
end while
Results post-processing
end

IV. SIMULATION RESULTS

The general scheme of partial shading condition is represented in Fig. 2. A study is carried out on MATLAB/Simulink software under PSP pattern. Panel layout with 5 bypass diodes shown in Fig. 3 has five PV modules connected in series and also is equipped with additive DC/DC converter.

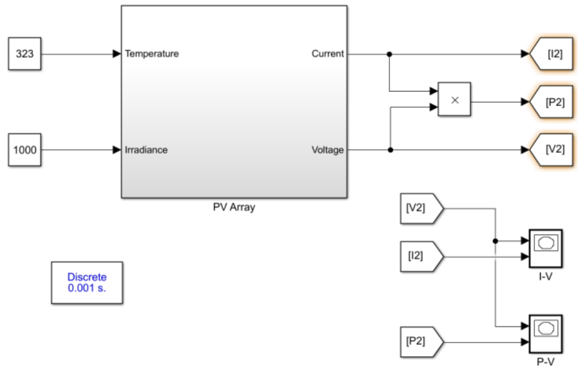

Fig. 2. General scheme of partial shading condition

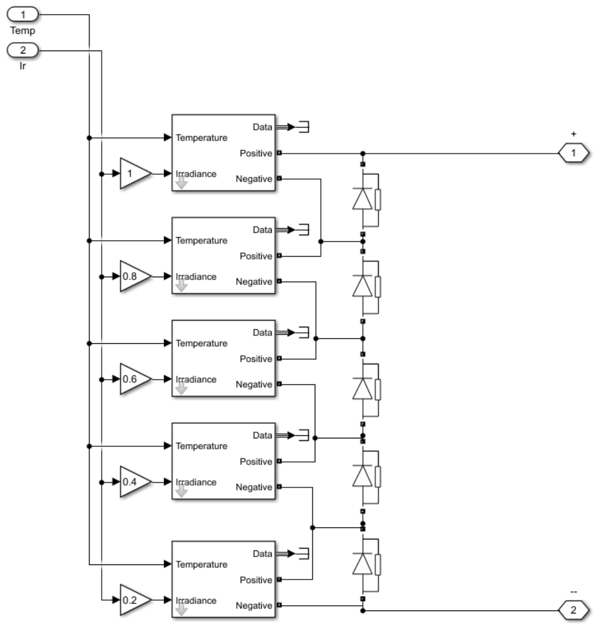

Fig. 3. Panel layout with 5 bypass diodes

The PV and IV curves of this configuration are represented in Fig. 4.

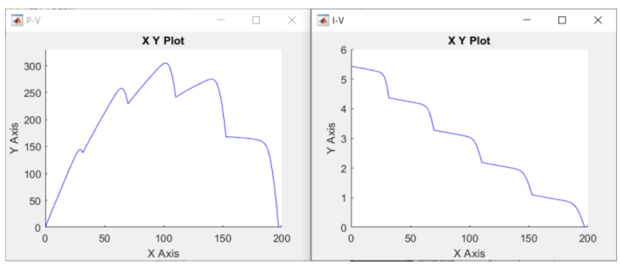

Fig. 4. PV and IV curves of this configuration

V. CONCLUSION

The Particle Swarm Optimization meta-optimized with Bat Search algorithm is proposed for maximum power point tracking under partial shading condition. Simulation results show that the proposed method is able to track global maximum power point under partial shading conditions.

REFERENCES

[1] V. M. Sineglazov, "Prospects for the development of the global electric power industry until 2035," *Electricity, transmission and distribution*. 2011, no. 2. p. 103.

[2] C. Tugcu, I. Ozturk, and A. Alper, "Renewable and non-renewable energy consumption and economic growth relationship revisited: Evidence from G7 countries," *Energy Economics*, vol. 34, Issue 6, November 2012, 1942 p. https://doi.org/10.1016/j.eneco.2012.08.021

[3] Javad Farzaneh, Reza Keypour, and Mojtaba Ahmadieh Khanesar, "A New Maximum Power Point Tracking Based on Modified Firefly Algorithm for PV System Under Partial Shading Conditions," *Technol Econ Smart Grids Sustain Energy*, 2018, 3:9. https://doi.org/10.1007/S40866-018-0048-7

[4] J. Wei, Y. Wang, and H. Wang, "A hybrid particle swarm evolutionary algorithm for constrained multi-objective optimization," *Computing and Informatics*, vol. 29, pp. 701–718, 2010.

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В. М. Синєглазов, Д. П. Карабецький, О. В. Клановець. Відстеження точки максимальної потужності для фотомодулей

Розглянуто проблему відстеження максимальної точки потужності для фотомодулів. Вирішення цієї проблеми базується на статичній параметричній мета-оптимізації для ройових алгоритмів. Для вирішення проблеми запропоновано алгоритм оптимізації рою частинок, мета-оптимізований за допомогою алгоритму пошуку кажана. Основна ідея алгоритмів полягає у тому, що вони складаються із базового алгоритму, який використовується для вирішення основного завдання оптимізації і мета-алгоритму, який використовується для пошуку оптимальної стратегії для базового алгоритму. Цільовою функцією базового алгоритму є цільова функція загальної задачі оптимізації. Мета-алгоритм оцінює цільову функцію, визначену для кожного покоління, і намагається мінімізувати її, шукаючи кращі стратегії базового алгоритму. Розглянуто приклад його застосування.

Ключові слова: відстеження точки максимальної потужності; фотоелектричні модулі; поновлювані джерела енергії; мета-алгоритм; алгоритм рою частинок; алгоритм пошуку кажана; оптимізація рою частинок.

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В. М. Синеглазов, Д. П. Карабецкий, А. В. Клановец. Отслеживание точки максимальной мощности для фотомодулей

Рассмотрена проблема отслеживания максимальной точки мощности для фотомодулей. Решение этой проблемы базируется на статической параметрической мета-оптимизации для роевых алгоритмов. Для решения проблемы предложен алгоритм оптимизации роя частиц, мета-оптимизированный с помощью алгоритма поиска летучей мыши. Основная идея алгоритмов заключается в том, что они состоят из базового алгоритма, который используется для решения основной задачи оптимизации и мета-алгоритма, используемого для поиска оптимальной стратегии для базового алгоритма. Целевой функцией базового алгоритма является целевая функция общей задачи оптимизации. Мета-алгоритм оценивает целевую функцию, определенную для каждого поколения, и пытается минимизировать ее, ища лучшие стратегии базового алгоритма. Рассмотрен пример его применения.

Ключевые слова: отслеживание точки максимальной мощности; фотоэлектрические модули; возобновляемые источники энергии; мета-алгоритм; алгоритм роя частиц; алгоритм поиска летучей мышей; оптимизация роя частиц.

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