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DEVELOPMENT OF AN IMPROVED HIERARCHICAL CONTROL SYSTEM USING THE METAHEURISTIC PID TUNER FOR DC MICROGRIDS

Abstract. This paper presents the development of the improved hierarchical control system using the metaheuristic centralized PID tuner for DC microgrids. Hierarchical control is one of the best control strategies employed in photovoltaics (PV) based DC microgrids with three layers of primary, secondary, and tertiary controllers in which PID control is at the center of each one of these three layered control levels. The principal objective of the primary controller is to ensure near-equal power sharing among the units and of the secondary controller is to correct the deviations in the common DC link, while the tertiary controller is used to manage the energy flow among DC microgrids or between DC microgrid and the main utility grid. Partial shading, the uncertain nature of solar irradiation, and varying temperatures significantly reduce the overall power efficiency of traditionally tuned PID control-based hierarchical systems, since the tuning gains of these PID controllers are not adaptive to the dynamic processes. To optimize the control process, a novel hierarchical system is considered in which PID gains of primary, secondary, and tertiary controllers are tuned with metaheuristic moth-flame optimization to adapt to the variations. Matlab/Simulink simulations are performed to verify the efficiency of the proposed approach. The results highlight the superiority of the proposed method by utilizing process adaptive gains.

Keywords: Hierarchical control system; DC-DC converters; DC microgrid, Metaheuristic; Moth flame optimization.

Introduction

A growing interest in DC microgrids, which is an electrical network integrating various distributed energy sources, has led to the development of more energy-efficient and reliable microgrids and the source of this significant interest is the high efficiency of the DC microgrids compared to the AC microgrids. The fundamental advantages of DC microgrids are the following [1]:

1) non-existence of reactive power;
2) no need for additional DC-AC conversion for PV units;
3) no need for frequency synchronization;
4) no need for the AC-DC conversions for battery energy storage packs.

A fundamental small-scale DC microgrid, which is shown in Fig. 1, is composed of the power generation units, which in our case they are the photovoltaic (PV) units, parallel linked DC-DC converters, batteries for energy storage, and DC-AC inverters for the AC loads [2].

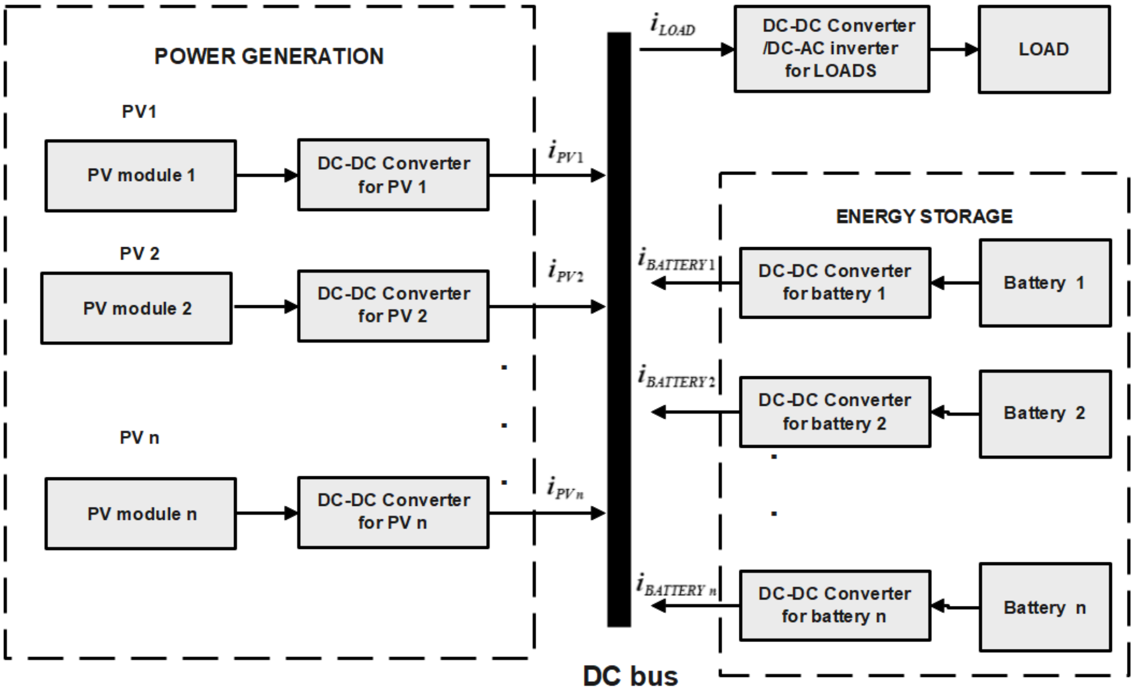


Fig. 1. Simple photovoltaic DC microgrid

PV-based DC microgrids are popular in the field and are considered to be the main supply of the microgrid. However, PV units are susceptible to the following issues [3]:

1) varied levels of solar irradiation;
2) partial shading conditions;
3) temperatures;
4) manufacturing imperfections.

The above-mentioned factors cause the output power and voltage of PV modules to vary, which necessitate the usage of DC-DC converters. The principal purpose of the DC-DC converters is to regulate the output voltage when the input voltage of the converter is unregulated. These converters, which are controlled by PID controllers, are utilized between PV units and DC common bus, battery units and common bus, load, and common bus.

Analysis of publications. Overall, centralized [4-8], decentralized [9-13], distributed [14-19], and hierarchical [20-22] control systems are the fundamental DC microgrid control strategies.

Observability and controllability are prime advantages of central controllers, while these controllers lack flexibility and expandability. Decentralized controllers are advantageous in having no communication links among the units. However, lack of coordination is the main challenge. The advantages of centralized and decentralized controllers can be merged into distributed control systems. However, the complicated design of systems could make it impractical. Hierarchical control strategy integrates all the positive sides of centralized, decentralized, and distributed controllers.

At the heart of these controllers are PI/PID controllers. Traditional PID controllers [23] require a time-consuming tuning process. The increased number of the converters requires tuning of the multiple converters which can be time-consuming and inefficient given all non-ideal characteristics.

Purpose and problem statement. The article aims at developing a new hierarchical control system with a metaheuristic moth-flame optimized PID controllers for the primary, secondary, and tertiary controllers to obtain higher efficiency.

Research results

MFO Algorithm. A metaheuristic population-based moth flame optimization was extensively applied and studied, especially in power electronics, since the year it was presented in 2015. Population-based algorithms initially generate a “population’’ of the potential solutions to the given problem, which accelerate the total search speed. It also boosts the local optima avoidance capability of the controller. This optimization technique was inspired by the moth’s navigation capability to find its way by adjusting its angle with the moon.

However, around the human-made light sources, they are easily trapped in the spiral trajectory, ending up in a lock around the light source.

The MFO follows the fundamental patterns of the metaheuristic algorithms. It starts the optimization process with the random initialization process of the moths with the P matrix and evaluation function array of OP with the dimension d and flame number n [24].

$$G = \begin{pmatrix} g_{11} & g_{12} & \cdots & g_{1d} \\ g_{21} & g_{22} & \cdots & g_{2d} \\ \cdots & \cdots & \cdots & \cdots \\ g_{n1} & g_{n2} & \cdots & g_{nd} \end{pmatrix}; \qquad (1)$$

$$OG = \begin{pmatrix} OG_1 \\ OG_2 \\ \vdots \\ OG_n \end{pmatrix}. \qquad (2)$$

Initial moths (potential solutions) are produced using the following equation:

$$G_{ij} = \left(UB(i) - LB(i)\right) rand() + LB(i) . \qquad (3)$$

The next component to be initialized is the flame B and its corresponding evaluation function matrix OB:

$$B = \begin{pmatrix} B_{11} & B_{12} & \cdots & B_{1d} \\ B_{21} & B_{22} & \cdots & B_{2d} \\ \cdots & \cdots & \cdots & \cdots \\ B_{n1} & B_{n2} & \cdots & B_{nd} \end{pmatrix}; \qquad (4)$$

$$OB = \begin{pmatrix} OB_1 \\ OB_2 \\ \vdots \\ OB_n \end{pmatrix}. \qquad (5)$$

The flame matrix denotes the best solutions obtained at the current iteration.

The logarithmic spiral function is preferred to update the potential solutions for the next iteration.

$$S\left(G_i, B_j\right) = \left|B_j - G_j\right|_i e^{bt} \cos(2\pi t) + G_j . \qquad (6)$$

A simplified pseudocode for MFO is shown in Listing 1.

```
initialization
for i=1 to n do
    the evaluation function computation
while iteration ≤ Max iteration do
    update P(i)
    Compute the flame number
    Compute evaluation function OG
    if  iteration==1 then
        B=sort(G) and OB=sort (OG)
    else
        B=sort (P(i-1), P(i)) and OB=sort (P(i-1), P(i))
    end if
    for i= to n do
        for i=1 to d do
            G (i, j) update
        end for
end while
```

Listing 1 – Simplified Pseudo-code for MFO

Traditional PID control. The design of the traditional PID controller is performed to compare the results with the enhanced MFO-PID controller of the DC microgrid. These controllers are widely adopted in

DC microgrids owing to their efficiency and easy implementation. Three main terms are associated with the PID controller and the total mathematical formula of PID control is the following:

$$u(t)=K_p e(t)+K_i\int e(t)dt+K_d\frac{de(t)}{dt}, \qquad (7)$$

where $u(t), K_p, K_i, K_d$ are PID's control signal, proportional, integral and derivative gains.

The error is the difference between the desired and actual value. The famous PID control strategy is Ziegler Nichols method. This method starts the tuning process by setting all gains to zero except for the proportional gain, following which the proportional is artificially increased and stopped when the system is unstable. The frequency of the oscillations the maximum proportional gain is measured and gains are calculated. The detailed methodology is presented in [25].

The trial and error method is utilized with the Ziegler Nichols method to obtain satisfactory performance.

Proposed Strategy. An improved hierarchical control system is proposed with metaheuristic algorithms and is depicted in Fig. 2. With the help of three fundamental controllers, which are primary, secondary, and tertiary controllers, superior control can be obtained.

Primary Controllers. Obtaining optimal current sharing at the output stages of the converters is of paramount importance. Small variations in the output voltages can produce the circulating currents which could fail some of the converters. Primary controllers are employed for this purpose to balance the output currents. A lot of topologies have been adopted to overcome this problem, among which the droop control strategy is one of the most employed control systems. The droop control strategy is based on the presence of virtual resistance, which is not a real resistance, to reduce the output voltage, while increasing the current. The mathematical model is of the following form:

$$V''_{O.REF.J}=V_{MG.REF}-I_J R_{dj}\,. \qquad (8)$$

where $V_{MG.REF}, I_J, R_{dj}$ are the reference voltage, converter load current, and virtual resistance values, respectively.

However, the current regulation can come at a cost of voltage deviation at the output stage.

At the primary controller stage voltage and inner current loop, controllers exist.

The error voltage for the voltage controller is:

$$e_{o.j.V}=V''_{O.REF.J}-V_{o.j}\,; \qquad (9)$$

$$I_{\mathrm{Re}\,ference}=K_p(e_{o.j.V})+$$
$$+K_i\int(e_{o.j.V})dt+K_d\frac{d(e_{o.j.V})}{dt}. \qquad (10)$$

The error voltage is fed to the first voltage mode PID controller, the output of which determines the reference voltage for the inner loop current controller:

$$e_{o.j.I}=I_{REF}-I_j\,. \qquad (11)$$

The output of the current controller is

$$I_{regulated}=K_p(e_{o.j.I})+$$
$$+K_i\int(e_{o.j.I})dt+K_d\frac{d(e_{o.j.I})}{dt}. \qquad (12)$$

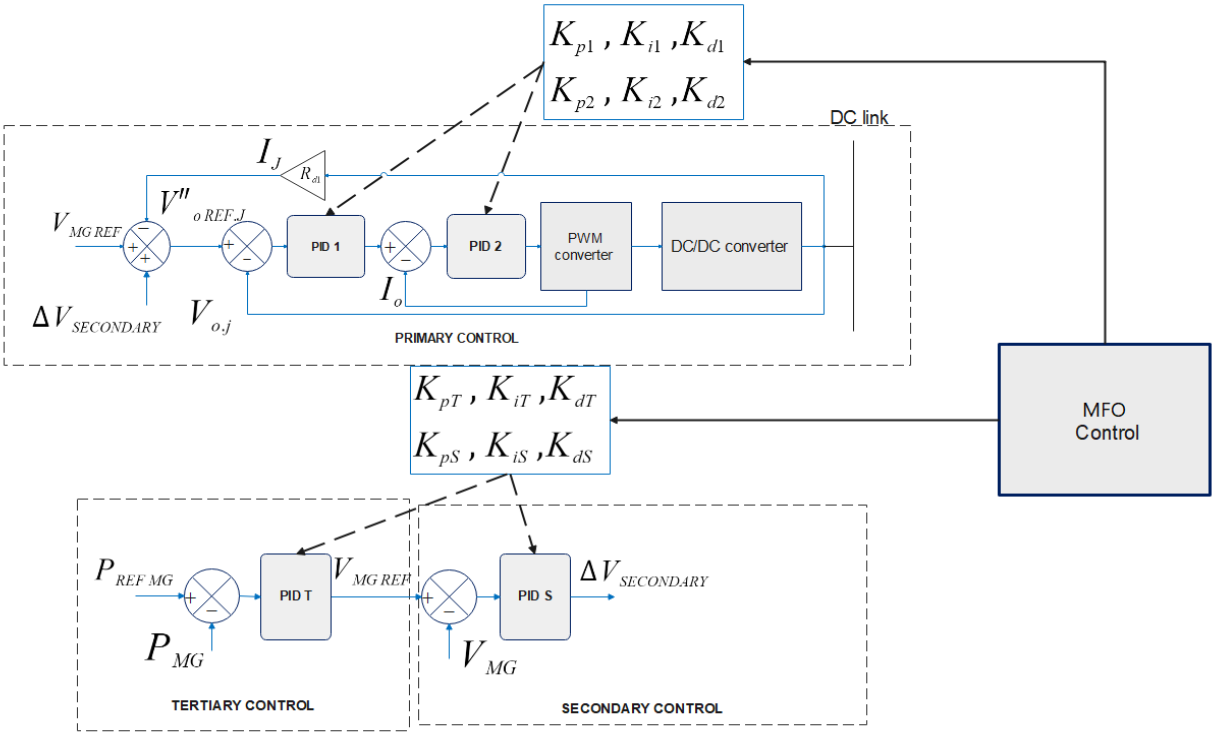


Fig. 2. Proposed control method for DC microgrid

Secondary Controllers. To offset the voltage deviation in the DC link caused by the droop-based primary controllers, secondary controllers are necessary. PID controllers offer simpler and more effective control action and are used:

$$e_{o.j.S} = V_{MG.REF} - V_{MG}\ ; \tag{13}$$

$$\Delta V_{secondary} = K_p(e_{o.j.S}) + \\ + K_i \int (e_{o.j.S})dt + K_d \frac{d(e_{o.j.S})}{dt}. \tag{14}$$

Tertiary Controllers. Tertiary control is the highest level control and functions as an energy flow controller among DC micrograms or between DC microgrid and the main grid.

$$e_{o.j.P} = P_{REF.MG} - P_{MG}\ ; \tag{15}$$

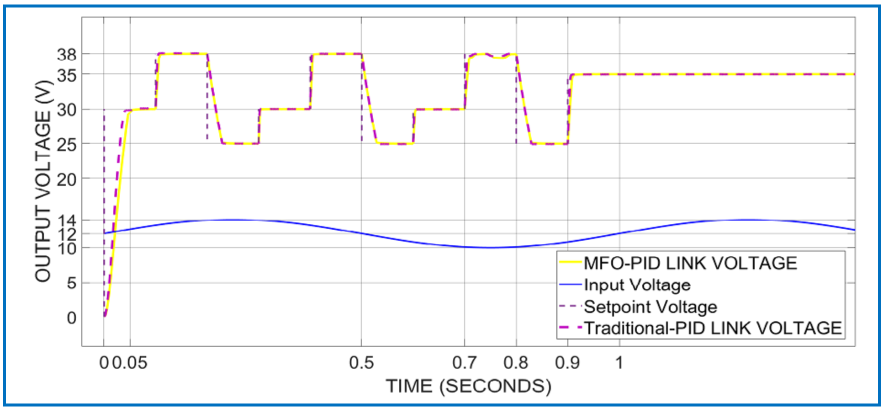
$$V_{MG.REF} = K_p(e_{o.j.P}) + \\ + K_i \int (e_{o.j.P})dt + K_d \frac{d(e_{o.j.P})}{dt}. \tag{16}$$

Simulation results. Simulations are carried out under varying setpoint voltages and input voltages.

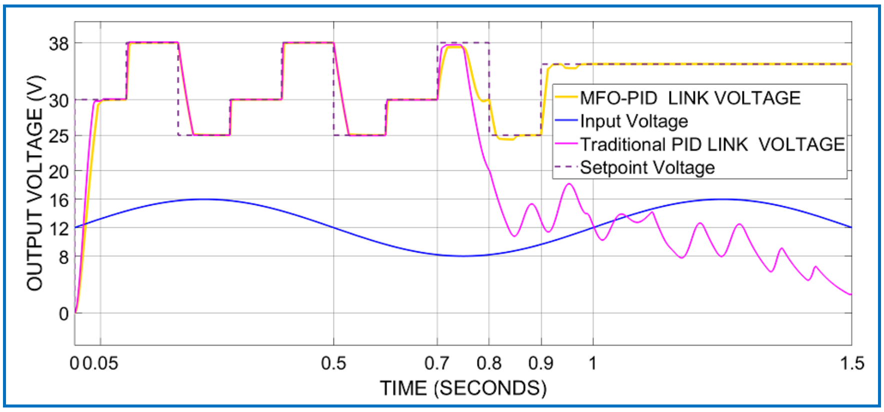
In the first case, which is shown in Fig.3 (a), the input voltage of the DC-DC converters fluctuate between 10V to 14V with 12V DC bias voltage and 2V variation voltage imitating uncertain nature of the PV units. Setpoint voltages take the following values [30, 38, 25, 30, 38..35]. The output load is selected to be 7Ω. As is clear from the graph, the converters with both traditional PID and MFO-PID controllers track the varying setpoint voltages closely.

In the second case, which is shown in Fig. 3 (b), the input voltage variation is increased to 4V with 12V DC bias voltage, which changes the input voltage from 8V to 16V. The load and setpoint voltages are the same as in the previous case. The added variation puts increased stress on the converters. As is clear from the graph, the traditional PID controller was not capable of showing robust performance and it destabilized at time 0.75s. However, MFO optimized controller continued to track the setpoint voltages.

A similar pattern also exists for the power in the DC link in Fig. 4 (a) and Fig.4 (b).



a – 2V input variation



b – 4V input variation

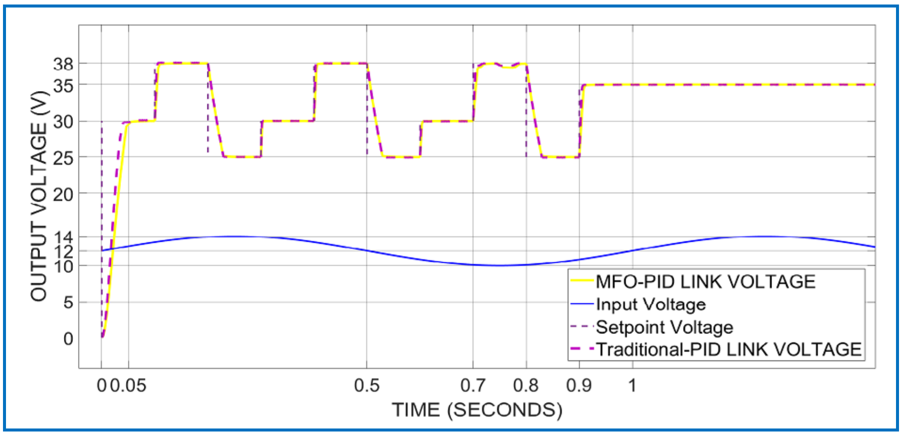
Fig. 3. DC link voltage

Conclusions

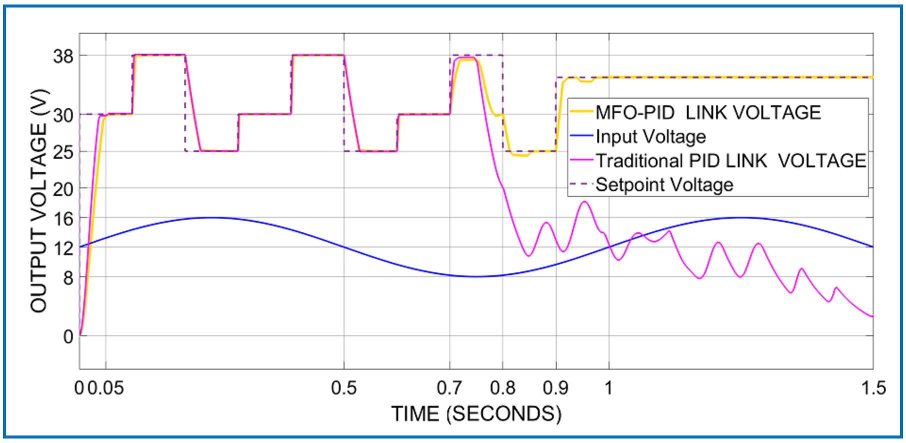
An optimized DC microgrid hierarchical control system whose PID controllers are adaptively tuned is proposed in this paper. The centralized MFO-PID tuner is designed and implemented for the tuning of all PID controllers in DC microgrid. The results are compared with the traditional tuning methods, outcomes of which verified the superiority of the proposed approach by increased robustness in DC link voltage.

Conflict of interest

The authors state that there is no conflict of interest regarding the publication of this article.



a – 2V input variation



b – 4V input variation

Fig. 4. DC link power

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Розробка ієрархічної системи управління з використанням метаевристичного ПІД-регулятора для мікромереж постійного струму

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Анотація. У цій статті представлено розробку вдосконаленої ієрархічної системи управління з використанням метаевристичного ПІД-регулятора для мікромереж постійного струму. Ієрархічне управління є однією з кращих стратегій управління, що використовуються в мікромережах постійного струму на основі фотоелектричних елементів (PV) з трьома рівнями первинних, вторинних та третинних контролерів, в яких ПІД-регулювання знаходиться в центрі кожного з цих трьох рівнів управління. Основним завданням основного контролера є забезпечення приблизно рівного розподілу потужності між блоками, вторинного контролера – корекція відхилень у спільній ланці постійного струму, а третинний контролер використовується для управління потоком енергії між блоками постійного струму мікромереж або між мікромережею постійного струму та основною комунальною мережею. Часткове затінення, невизначений характер сонячного випромінювання та мінливі температури значно знижують загальну енергоефективність ієрархічних систем на основі традиційно налаштованого ПІД-регулятора, оскільки коефіцієнти налаштування цих ПІД-регуляторів не адаптуються до динамічних процесів. Для оптимізації процесу управління розглядається нова ієрархічна система, у якій коефіцієнти ПІД-регулювання первинних, вторинних та третинних регуляторів налаштовуються за допомогою метаевристичної оптимізації для адаптації до змін. Моделювання Matlab/Simulink виконується для перевірки ефективності запропонованого підходу. Результати підкреслюють перевагу запропонованого методу за рахунок використання адаптивних переваг процесу.

Ключові слова: ієрархічна система управління; перетворювачі постійного струму; мікромережа постійного струму; метаевристика.