A Distributed Stabilizing Economic Dispatch Control for Energy Storage Unit based Autonomous Microgrid

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Abstract— **In this paper, a fully distributed control-based consensus method is used to ensure a stabilizing Economic Dispatch (ED) for different Distributed Energy Storage System (DESS) technologies while achieving frequency and voltage regulation of Distributed Generators (DGs). All DESSs, as agents, work together to minimize the total generation cost (TGC) of the islanded Microgrid (MG) by applying the principle of equal incremental cost in the consensus algorithm. The consensus algorithm provides the optimal active powers to all DGs which are sent to the droop control. These optimal active power references are chosen to regulate the DG frequency to the nominal frequency of the MG. Therefore, the proposed method ensures optimal economic dispatch with automatic frequency restoration. A MATLAB/Simulink simulation is performed in order to verify the effectiveness of the proposed method in case of load variation. A comparison between the proposed ED method and the ED control used in a decentralized architecture controller is also provided to show the contributions of the proposed method.**

Keywords— Consensus control, Distributed Energy Storage System, Distributed Generation, Economic Dispatch, Secondary control

I. INTRODUCTION

Microgrids (Fig. 1) represent the most promising solution to meet the environmental and energy security requirements of the energy transition. In fact, MGs facilitate the integration of Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs). The association of ESSs and RESs is a promising approach to improve the MG operation, energy quality, and stability. The most widely used type of ESS in MG application are Battery Energy Storage Systems (BESSs) due to their long-term application capability, fast dynamic response and energy absorption/release at an acceptable cost [1]. Traditionally, droop control is used to share the active power of DGs proportionally to their power rating. This type of control is not suitable for MG involving different battery technologies where other factors such as generation cost, maintenance cost, no-load cost must be considered. In this case, an economic dispatch control should be applied to minimize the TGC of the MG.

Classically, centralized approach methods such as lambda iteration method, linear programming, hybrid immune algorithm and particle swarm optimization are implemented to minimize the MG TGC. However, these centralized controls have many drawbacks, including single point of failure, high cost of communication infrastructure, delay etc. Nowadays, distributed control based on Multi-Agent Systems (MAS) [2], [3] and decentralized control [4], [5] which are more reliable, are used for economic dispatch. In distributed approach, the interactions between DGs are considered while in decentralized control these interactions are neglected. In [6], a droop scheme method based on decentralized control is used to ensure economic dispatch. The author takes advantage of the fact that frequency is a common variable in the MG to apply the principle of cost equality and reduce the TGC. However, frequency and voltage restoration of the DGs is not investigated. This restoration allows to correct the frequency and voltage deviations induced by the droop control. References [7], [8] and [9] propose distributed control-based consensus for economic dispatch. By using the incremental cost as the consensus value, these consensus algorithms can minimize the TGC of the MG through the principle of equal incremental cost. But no information on the frequency and voltage variations of the DGs has been presented in [7] and [8]. In [9], the restoration of the frequency and voltage of the DGs to their nominal values is not studied.

In all the strategies presented above, the DG frequency and voltage restoration is either omitted or not studied. This may lead to stability problems especially since these strategies are implemented with droop control which causes frequency and voltage deviations from their nominal. Therefore, an economic dispatch method to ensure an optimal active power control while ensuring DG frequency and voltage restoration is needed.

In this paper, a fully distributed control-based consensus method is used for an effective optimal active power control in order to minimized the TGC of an AC islanded microgrid involving DESSs with different production costs. The proposal achieves ED and frequency restoration with high resilience under constraining operating conditions (load variations) and with high performance. Beyond the power quality aspects, such an optimal active power control will allow a better exploitation of DESSs, leading to a better lifespan of these elements. Functionally, the design of the secondary level algorithm uses optimal active power references that are sent to the primary level to achieve the ED. The optimal active powers are determined by the consensus algorithm which is based on the principle of equal incremental cost to minimize the TGC of the Microgrid using the incremental cost as the consensus value with feedback on the difference between energy production and demand to ensure the balance between demand and production. In addition, the optimal active power references are chosen to stabilize the DGs frequency at the nominal frequency of the MG. Thus, the DG frequency is instantly restored to its nominal value without any additional control for the frequency restoration. Only voltage restoration control is implemented. The main contributions of this proposal are as follows:

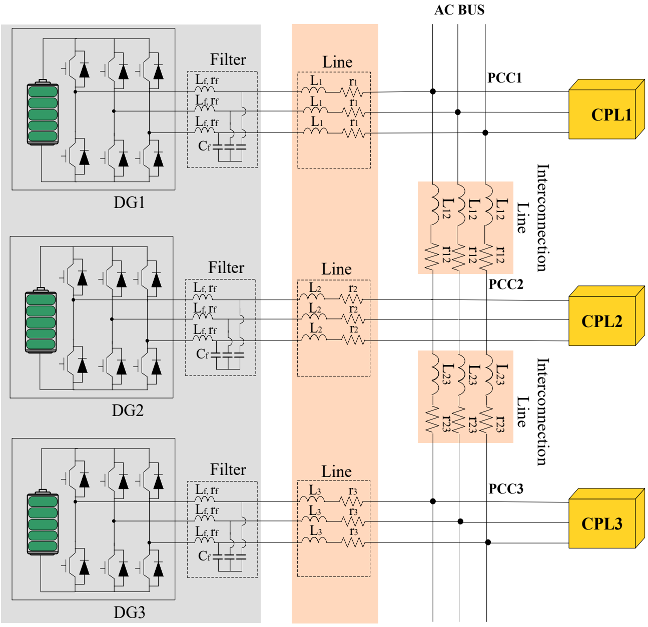

Fig. 1. Studied System

1) A distributed control-based consensus method is used for an effective optimal active power control in order to minimized the TGC of the MG involving DESSs.
2) Unlike what is done in the literature, the restoration of the voltages and frequencies of the DGs is achieved in this control.
3) Frequency correction is automatically performed in this proposal without the use of additional control laws, as the secondary control provides the primary levels with the proper optimal active power reference that fixes the DG frequency at the nominal value.

The rest of the paper is organized as follows: In Section 2 the studied system is presented. Section 3 discusses the stabilizing economic dispatch method. Simulation results are presented in Section 4 and Section 5 concludes this paper.

II. STUDIED SYSTEM DESCRIPTION

The general synoptic scheme of the studied system is presented in Fig. 1. This system represents an AC microgrid consisting of three batteries feeding three variable loads. Each load is connected to a local point of common coupling and the AC Microgrid is operating in islanded mode. In the next section, the stabilizing economic dispatch method is presented.

III. STABILIZING ECONOMIC DISPATCH STRATEGY

A. Graph Theory

The communication network can be expressed by a graph G= (V, E), with $V = \{v_1, v_2, \dots, v_N\}$, the set of N nodes or N agents and E$\subseteq V \times V$, the set of edges or arcs. Elements of E are denoted as (v_i, v_j) and represent the arcs from node v_i to node v_j and are represented with arrows at unique or double direction depending on the information flow between the two agents (unidirectional or bidirectional) as represented in Fig. 2.

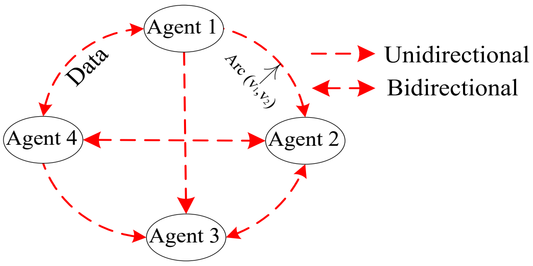

Fig. 2. Graph with four agents.

Each edge (v_i, v_j) is associated with a weight $a_{ij}>0$ if v_i receives information from v_j else$a_{ij} = 0$.

Considering the study system as strongly connected, the Laplacian matrix L= $[l_{ij}]$ is defined by the average Metropolis proposed in [10] which ensures the fast convergence of the consensus algorithm while guaranteeing its stability.

$$l_{ij} = \begin{cases} \dfrac{2}{n_i + n_j + \varepsilon} & j \in N_i \\ 1 - \displaystyle\sum_{j \in N_i} \dfrac{2}{n_i + n_j + \varepsilon} & i = j \\ 0 & else \end{cases} \tag{1}$$

with ε, a small number that can be considered as zero for large and complex systems. n_i and n_j represent the number of agents connected to agent i and agent j respectively.

Generally, the discrete consensus algorithm for updating the state of agent i, is as follows:

$$x_i[k+1] = \sum_{j=1}^{N} l_{ij} x_j[k] \tag{2}$$

with $x_j[k]$, the local information of agent j at iteration k, $x_i[k+1]$ represents the state of agent i at iteration k+1. N is the number of DGs.

For a strongly connected graph, the algorithm above achieves consensus [7]. Next, the problem of economic dispatching in a MG is studied.

B. ED Problem Definition

The cost function of DGs is usually represented by a quadratic function written as [9]:

$$\begin{cases} C_i(P_i) = \dfrac{a_i {P_i}^2}{2} + b_i P_i + c_i \\ {P_i}^{min} \leq P_i \leq {P_i}^{max} \end{cases} \tag{3}$$

$a_i > 0, b_i \ and \ c_i \geq 0$ represent the cost function coefficients, $C_i(P_i)$ represents the cost function, P_i is the active power, ${P_i}^{min}$ is the minimum active power and ${P_i}^{max}$ is the maximum active power of the DG_i.

This cost function usually includes generation cost, maintenance cost, no-load cost, fuel cost and emission penalty cost. Since the storage units have neither fuel cost nor emission penalty cost, their cost functions can be represented as the following [9]:

$$\begin{cases} C_i(P_i) = \dfrac{a_i {P_i}^2}{2} \\ {P_i}^{min} \le P_i \le {P_i}^{max} \end{cases} \tag{4}$$

The objective of economic dispatching is to minimize the global cost of power generation of the MG and can be represented by:

$$\begin{cases} \min(\sum_{i=1}^{N} C_i(P_i)) \\ \sum_{i=1}^{N} P_i = P_D + P_{loss} \\ P_i^{min} \le P_i \le P_i^{max} \end{cases} \tag{5}$$

P_D is the total active power of the load and P_{loss} represents the power lost in the MG.

The incremental cost of DGi is determined as follows:

$$\lambda_i = \frac{\partial C_i(P_i)}{\partial P_i} = a_i P_i \tag{6}$$

A solution to the economic dispatching problem is the equal incremental cost principle which states that the total production cost of the MG is minimized if all DGs in the MG have the same incremental cost, in other words $\lambda_1 = \lambda_2 = \lambda_3 = \cdots = \lambda_N = \lambda^*$, where λ^* is the optimal incremental cost.

C. *Proposed ED Strategy*

The proposed consensus algorithm used to calculate the optimal active power references of the DESSs considering the generation constraints is as follows:

$$\begin{cases} \lambda_i(k+1) = \sum_{j \in \mathcal{N}_i} l_{ij}\lambda_j(k) + K_D P_{Di}(k) \\ P_{iopt}(k+1) = \begin{cases} P_i^{min}, \lambda_i(k+1) < \lambda_i^{min} \\ \dfrac{\lambda_i(k+1)}{a_i}, \lambda_i^{min} \le \lambda_i(k+1) \le \lambda_i^{max} \\ P_i^{max}, \lambda_i(k+1) > \lambda_i^{max} \end{cases} \\ P_{Di}(k+1) = \sum_{j \in \mathcal{N}_i} l_{ij} P_{Dj}(k) - \left[P_{iopt}(k+1) - P_{iopt}(k)\right] \end{cases} \tag{7}$$

with $\lambda_i(k)$, $P_{iopt}(k)$, the incremental cost and the optimal active power of the DG_i respectively at iteration *k*; $P_{Di}(k)$ represents the power difference between the load power and the power generated by the DG_i and K_D is the ED consensus coefficient. In order to ensure the convergence of such a consensus algorithm, the ED consensus coefficient must be chosen sufficiently small [7], [9]. The design methodology of the gain has already been discussed in [7] and therefore will not be discussed in this paper.

Once the optimal active power references of the DGs are obtained, they are sent to the droop control. Thus, the global dynamic equation of the proposed stabilizing economic dispatch is reported in (8).

$$\omega_i = \omega_n - m_i(P_i - \boldsymbol{P_{iopt}}) \tag{8}$$

with ω_n, $m_i = \frac{\Delta\omega}{P_{in}}$, P_i, P_{in} are respectively the MG nominal frequency, the frequency droop coefficient, the DG_i active power and the nominal DG_i active power. $\Delta\omega$ is the maximum deviation of the frequency.

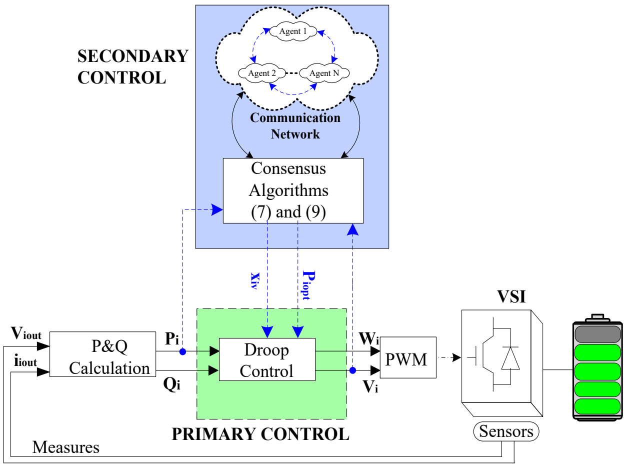

Fig. 3. DG control scheme

A stabilization of the DG_i frequency is achieved automatically in the investigated system, since the secondary control provides to the primary levels the appropriate active power references ($P_i = P_{iop}$) that stabilizes the frequency at its nominal value f_n. Therefore, either in the presence of sudden load variations, the control enables fast disturbance rejection with reduced impact on the frequency.

Regulation of the DGs voltage is achieved by means of a consensus control which principle is detailed in (9).

Equations for the distributed control-based consensus for voltage restoration are designed as follows:

$$\dot{X_v} = K_v\left(-L\bar{V} + B(\bar{V_n} - \bar{V})\right) \tag{9}$$

with $X_v = \begin{pmatrix} x_{1v} \\ \cdots \\ x_{Nv} \end{pmatrix}$; $\bar{V} = \begin{pmatrix} V_1 \\ \cdots \\ V_N \end{pmatrix}$; $\bar{V_n} = \begin{pmatrix} V_n \\ \cdots \\ V_n \end{pmatrix}$;

with K_v: voltage consensus control gain; L: Laplacian matrix; B= $diag\{b_i\}$: diagonal pinning matrix where b_i>0 if the agent v_i has the information about the consensus value, otherwise $b_i = 0$. x_{iv} represents the voltage compensator of the DG_i.

The dynamic equation for voltage control is represented as follows:

$$V_i = V_n - n_i(Q_i - Q_{in}) + \boldsymbol{x_{iv}} \tag{10}$$

with $V_n, n_i = \frac{\Delta V}{Q_{in}}, Q_i, Q_{in}$ are respectively the MG nominal voltage, the voltage droop coefficient, the DG_i reactive power and the DG_i nominal reactive power. ΔV represents the maximum deviation of the voltage.

The global control scheme of the stabilizing economic dispatch for a DG is reported in Fig 3.

IV. SIMULATIONS AND RESULTS

To investigate the proposed optimal active power strategy for MG based on DESSs, a MATLAB/Simulink simulation is performed on the studied system reported in Fig. 1. The MG

System parameters are reported in Table 1. The information flow between the agents is illustrated in Fig. 4. In order to show the effectiveness of the proposed stabilizing ED method for the DESSs generation cost minimization, the proposal is compared with the ED method used in [6] and the conventional droop control.

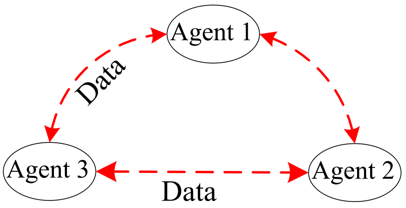

Fig. 4. Communication network topology.

TABLE I MG system parameters

Item	Symbol	Value
Line DG1	r_1, L_1	0.1Ω, 1mH
Line DG2	r_2, L_2	0.2Ω, 2mH
Line DG3	r_3, L_3	0.3Ω, 3mH
Line DG1-2	r_{12}, L_{12}	0.1Ω, 1mH
Line DG2-3	r_{23}, L_{23}	0.1Ω, 2mH
Rated power DG1	P_{1n}, Q_{1n}	4000 W, 3000 VAR
Rated power DG2	P_{2n}, Q_{2n}	4500 W, 1500 VAR
Rated power DG3	P_{3n}, Q_{3n}	5000 W, 1000 VAR
Capacity of the DESSs	μ	$50000(\mathrm{Ah.V})^{-1}$
MG frequency/voltage	f_n/V_n	50 Hz/230V
Max f & V deviation	Δ_f/Δ_V	0.5 Hz/5V
ED consensus coefficient	K_D	0.02
Cost function coefficients	a_1, a_2, a_3	0.07, 0.106, 0.192
Voltage consensus gain	K_v	10

The simulation results are presented in Fig. 5. The loads active powers are presented in Fig. 5 (a), the TGC of the MG for the three controls (proposed method, decentralized method used in [6]and droop control) is illustrated in Fig. 5 (b), DGs active powers and incremental costs for both ED controls (proposed method, decentralized method) are represented in Fig. 5 (c), Fig. 5 (d) and Fig. 5 (e), Fig. 5 (f) respectively, frequency and voltage of the DGs for both ED controls (proposed method, decentralized method) are represented in Fig. 5 (g), Fig. 5 (h) and Fig. 10 (i), Fig. 5 (j) respectively.

It can be seen in Fig. 5 (b) that the TGC of the MG is minimized for the proposal and the decentralized control used in [6] compare to the conventional droop control. The equal incremental cost principle is well achieved in both ED controls (Fig. 5 (c) and Fig. 5 (d)). In both ED controls, each DESS supplies active power to the grid according to its cost function resulting a minimization of the TGC of the MG as represented in Fig. 5 (e) and Fig. 5 (f). However, Fig. 5 (h) shows that the DGs frequencies are not restored to their nominal values and change with load variations. Whereas with the proposed stabilizing economic dispatch strategy, the DGs always operate at nominal frequency (50 Hz) even with load variations as shown in Fig. 5 (g) without using additional control for frequency regulation. DGs voltages are also not restored to their nominal values and change with load variations as reported in Fig. 5 (j). While with the proposal, the DGs always operate at nominal voltage (230 V) even with load variations as shown in Fig. 5 (i). It is worth mentioning that frequency and voltage restoration can be achieved by adding a higher level of control for the decentralized control. However, this additional control could disrupt the economic dispatch strategy, especially for frequency restoration if the appropriate control is not used.

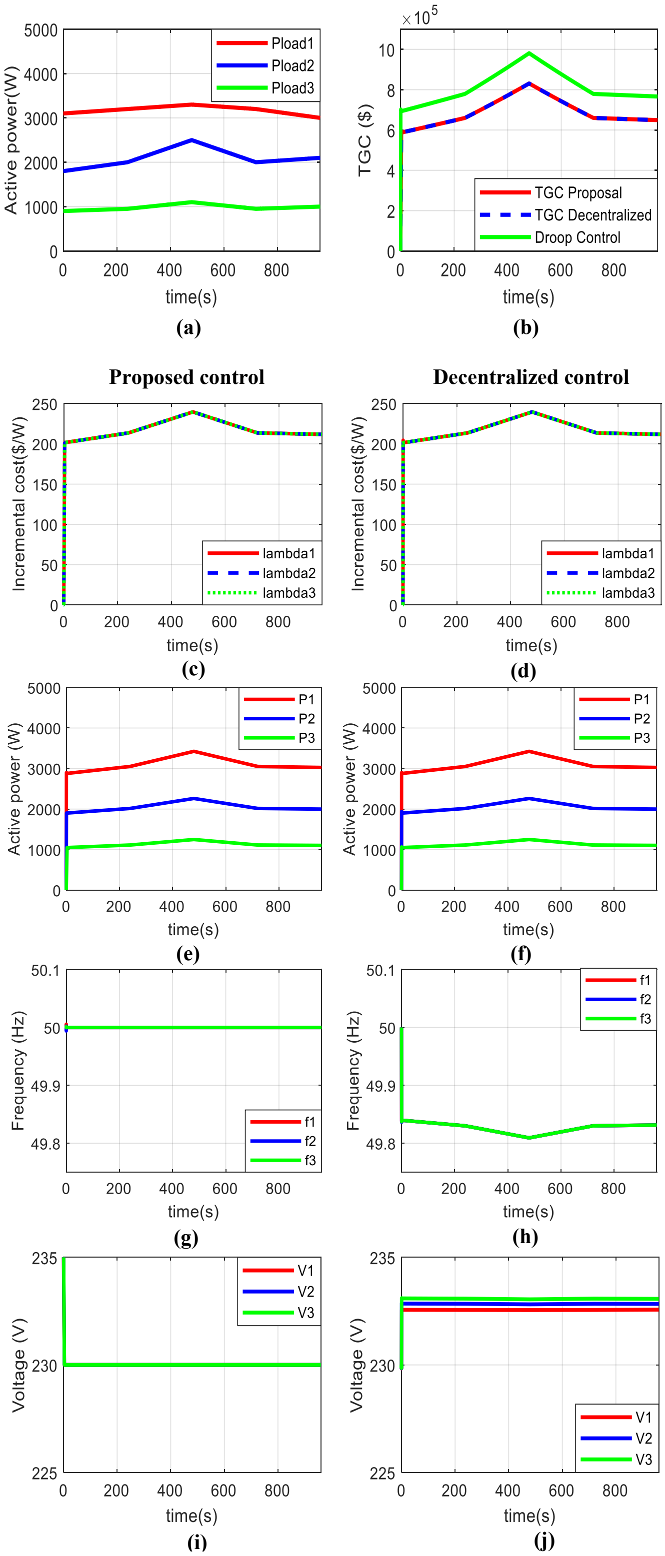

Fig. 5. Comparison with the decentralized strategy used in [6] and the droop control: (a) Loads active powers; (b) MG TGC for the proposal, the decentralized control and the droop control; (c) and (d) DGs active powers; (e) and (f) DGs incremental costs; (g) and (h) DGs frequencies; (i) and (j) voltages of the DGs for both controls.

V. Conclusion

This paper applies a distributed control-based consensus to ensure a stabilizing economic dispatch in an autonomous MG involving different DESS technologies. The proposed method minimizes the TGC of the MG while achieving frequency restoration without adding additional controls that could disrupt the economic dispatch strategy. Voltage restoration is also ensured thanks to a consensus control. The proposed stabilizing economic dispatch is validated through MATLAB/Simulink simulation and is compared to another ED control. The simulation results show the effectiveness of the proposed optimal power management control in load variations scenario and the contributions of the proposed stabilizing economic dispatch.

References

[1] C. Huang, S. Weng, D. Yue, S. Deng, J. Xie, et H. Ge, « Distributed cooperative control of energy storage units in microgrid based on multi-agent consensus method », Electric Power Systems Research, vol. 147, p. 213-223, juin 2017, doi: 10.1016/j.epsr.2017.02.029.

[2] A. Wang et W. Liu, « Distributed Incremental Cost Consensus-Based Optimization Algorithms for Economic Dispatch in a Microgrid », IEEE Access, vol. 8, p. 12933-12941, 2020, doi: 10.1109/ACCESS.2020.2966078.

[3] Q. Li, D. W. Gao, H. Zhang, Z. Wu, et F. Wang, « Consensus-Based Distributed Economic Dispatch Control Method in Power Systems », IEEE Transactions on Smart Grid, vol. 10, no 1, p. 941-954, janv. 2019, doi: 10.1109/TSG.2017.2756041.

[4] H. Xin, R. Zhao, L. Zhang, Z. Wang, K. P. Wong, et W. Wei, « A Decentralized Hierarchical Control Structure and Self-Optimizing Control Strategy for F-P Type DGs in Islanded Microgrids », IEEE Transactions on Smart Grid, vol. 7, no 1, p. 3-5, janv. 2016, doi: 10.1109/TSG.2015.2473096.

[5] I. U. Nutkani, P. C. Loh, P. Wang, et F. Blaabjerg, « Decentralized Economic Dispatch Scheme With Online Power Reserve for Microgrids », IEEE Transactions on Smart Grid, vol. 8, no 1, p. 139-148, janv. 2017, doi: 10.1109/TSG.2015.2451133.

[6] F. Chen et al., « Cost-Based Droop Schemes for Economic Dispatch in Islanded Microgrids », IEEE Transactions on Smart Grid, vol. 8, no 1, p. 63-74, janv. 2017, doi: 10.1109/TSG.2016.2581488.

[7] R. Wang, Q. Li, B. Zhang, et L. Wang, « Distributed Consensus Based Algorithm for Economic Dispatch in a Microgrid », IEEE Transactions on Smart Grid, vol. 10, no 4, p. 3630-3640, juill. 2019, doi: 10.1109/TSG.2018.2833108.

[8] G. Chen, F. L. Lewis, E. N. Feng, et Y. Song, « Distributed Optimal Active Power Control of Multiple Generation Systems », IEEE Transactions on Industrial Electronics, vol. 62, no 11, p. 7079-7090, nov. 2015, doi: 10.1109/TIE.2015.2431631.

[9] Y. Xu et Z. Li, « Distributed Optimal Resource Management Based on the Consensus Algorithm in a Microgrid », IEEE Transactions on Industrial Electronics, vol. 62, no 4, p. 2584-2592, avr. 2015, doi: 10.1109/TIE.2014.2356171.

[10] Y. Xu et W. Liu, « Novel Multiagent Based Load Restoration Algorithm for Microgrids », IEEE Transactions on Smart Grid, vol. 2, no 1, p. 152-161, mars 2011, doi: 10.1109/TSG.2010.2099675.