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Energy Management and Voltage Regulation of Grid-Connected Microgrid Using Genetic Algorithm

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Abstract –**This paper proposes a genetic algorithm-based optimization methodology that considers the voltage regulation in a grid-connected microgrid. The need for voltage regulation comes from the stochastic nature of the power consumption and the power generation from the distributed generators, and the need for a stable and quality power supply. The algorithm is tested on a small-scale microgrid with PV and wind generators, supported by a battery energy system over a 24-hour time period. The obtained results show the financial benefit of considering the voltage regulation as part of the optimization process.**

Keywords – r**enewable energy sources; microgrids; genetic algorithm; optimization.**

I. INTRODUCTION

The abandonment of the traditional centralized structure of the power system, as well as the higher standards for quality of electricity, actualize the implementation of renewable energy sources (RES). Supported by the idea of clean and environmentally friendly power generation and the accompanying financial benefit, RES are gradually but surely making their way as the leading source of energy.

The idea of decentralized electricity generation is increasingly present in the world. The formation of microgrids provides consumers with greater reliability in electricity delivery, lower costs and lower electricity losses. At the beginning of the realization of this idea, due to the simplicity of the microgrids, optimization was not inevitable. But today, when microgrids consist of many different distributed generators, more interconnected consumers, batteries, and backup generators (e.g. diesel generators, fuel cells), optimization is mandatory for the proper and balanced operation of the microgrid, due to the stability of the network and the system to which it is connected.

The microgrids that are connected to the local network are obliged to meet certain requirements regarding the amount of electricity they receive and transmit in the system. Therefore, it is of particular importance that the energy management system processes data in real time taking into account the following factors that may directly or indirectly affect the stability of the system: weather conditions, battery state of charge (SOC), the occurrence of an outage in the system, maintaining a stable voltage in the microgrid and the unpredictability of electricity demand.

In [1] the implementation of a hierarchical genetic algorithm for calculating the maximum benefit from the power trading between the microgrid and the local network, determining the price of electricity according to the time of use, is presented. In [2], an accelerated genetic algorithm is proposed to solve multi-objective optimization problems in a microgrid. The purpose function includes the costs of operation and maintenance of the microgrid, the cost of fuel for the diesel generator, and the cost of emissions during its use, as well as the cost of replacing the elements. In [3] a genetic algorithm is applied for optimal load distribution between wind generators, PV, batteries, and a diesel generator in the microgrid. In [4], to solve the problem of optimal optimization, an upgrade of the genetic algorithm for faster convergence is proposed. In [5] penal costs are introduced in a model based on a genetic algorithm. Voltage and frequency analysis using a genetic algorithm is presented in [5]. The reference [7] shows the simultaneous optimization of dispersed generation and energy storage systems in network-connected microgrids and standalone microgrids. The paper analyzes two alternative objective functions. The first minimizes annual power losses, and the second minimizes the cost of generating electricity. The reference [8] proposes a method based on multi-criterion optimization to encourage entities in the microgrid for maximum voltage control. The need for voltage and reactive power control in microgrids connected to a local distribution network is shown in [9].

The contribution of this research is from the aspect of reducing power losses and ensuring voltage stability, which results in minimizing the costs of providing electricity in the microgrid and maximizing the financial benefit from the produced electricity. The inclusion of penalty costs improves the reliability of electricity supply, but significantly complicates the optimization process. However, if the voltage in certain nodes in the microgrid is regulated, by optimizing the production of distributed generators and regulating the power flows, greater stability is provided and the penalty costs for not supplying electrical energy are decreased.

II. PROBLEM DEFINITION

Microgrids connected to the local utility grid have an advantage in the absence of electricity from the local network to supply consumers. However, the network connection bears a great responsibility in terms of voltage stability, and the operation of the microgrid should not affect the operation of the local network(s) to which it is connected, especially not the consumers. Therefore, the proper use and management of the power generated by the distributed generators and the one stored in the batteries is of great importance.

The Energy Management System (EMS) should ensure that the storage or sale of excess power to the local grid is in place at the right time while meeting the demand [10]. The problem with optimal usage of power generated by distributed generators, optimal battery usage, and trading with the local network is further complicated by taking into account the prices of electricity under different market oriented conditions [4]. This is the main difference between the unit commitment problem in the standard power system and in the microgrids.

III. PROBLEM SOLUTION

The proposed algorithm considers the stochastic nature of the weather conditions and the power demand. The optimization function takes into account the costs of buying electricity from the grid in case of shortage (C_{grid}) and the financial benefit from the production and sale of electricity to the grid (B_{DER}). The optimization function maximizes the profit from the operation of the microgrid, but also takes into account the penalty costs for not supplying power with a defined quality ($C_{penalty}$) or not supplying power at all.

The optimization function is shown in Eq. (1).

$$F(C) = \max\left\{\sum_{i=1}^{T}(B_{DER,i} - C_{grid,i})\Delta t - C_{penalty}\right\} \quad (1)$$

where T represents the analyzed time period.

The total benefit and the costs of the microgrid are shown in Eqs. (2) and (3), respectively

$$B_{DER,i} = P_{PV,i}\,p_{pv,i} + P_{wind,i}\,p_{wind,i} + P_{bat,i}\,p_{bat} \quad (2)$$

$$C_{grid,i} = P_{buy,i}\,p_{grid} \quad (3)$$

The benefit is calculated as the sum of the profit from generating power from the installed generators and selling the excess power in the local network and the cost of storing the excess power in batteries. The costs are presented as the costs for purchasing power from the network.

Penalty costs for not supplying or supplying substandard electricity with unstable voltage are calculated depending on the Energy Not Supplied (ENS) and duration of not supply:

$$C_{penalty} = f(E_{not\,supplied,i}, \Delta t) \quad (4)$$

The proposed method in this paper analyzes the costs in the microgrid and checks the voltage in the nodes, taking into account the technical limitations of the installed equipment. The maximum power generated by RES is represented by Eqs. (5) and (6), for PV and wind generators, respectively.

$$P_{PV,\min} \le P_{DER,i} \le P_{PV,\max}, \forall i \in [0,T] \quad (5)$$

$$P_{wind,\min} \le P_{DER,i} \le P_{wind,\max}, \forall i \in [0,T] \quad (6)$$

The maximum and minimum battery power as well as the SOC are represented by Eqs. (7) and (8).

$$0 \le P_{bat,i} \le P_{bat,\max}, \forall i \in [0,T] \quad (7)$$

$$0 \le SoC_{bat,i} \le 1, \forall i \in [0,T] \quad (8)$$

To maintain balance in the system, it is necessary to define the maximum and minimum power taken and injected into the network. This reduces the voltage variations that would occur due to a sudden decrease or increase of power in the system. These limits are regulated by the network to which the microgrid is connected. The technical limitations are represented by Eqs. (9) and (10).

$$0 \le P_{buy,i} \le P_{buy,\max}, \forall i \in [0,T] \quad (9)$$

$$0 \le P_{sell,i} \le P_{sell,\max}, \forall i \in [0,T] \quad (10)$$

The power balance equation is shown in Eq. (11), and the node voltage variation limits are shown in Eq. (12). Voltage variations in grid-connected low voltage microgrids with renewable energy sources are limited to a certain percentage in order to achieve better quality in power supply [11] [12].

$$\begin{aligned} &P_{PV,i} + P_{wind,i} + P_{bat\_dis,i} + P_{buy,i} = \\ &P_{load,i} + P_{sell,i} + P_{bat\_ch,i}, \forall i \in [0,T] \end{aligned} \quad (11)$$

$$Q_{bat\_dis,i} + Q_{buy,i} = Q_{load,i}, \forall i \in [0,T] \quad (12)$$

$$0.95 \cdot V_r \le V(t,i) \le 1.05 \cdot V_r, \forall i \in [0, n_{nodes}] \quad (13)$$

The voltage in each of the nodes is calculated by the expression (13). The voltage in the Point of Common Coupling (PCC) is considered a reference node.

$$V(t,i+1) = V(t,i) + \frac{\left(\sum P_i(t)\right)rl + \left(\sum Q_i(t)\right)xl}{V_n}, \forall i \in [0, n_{nodes}] \quad (14)$$

Where, *V(t, i)* denotes the voltage in the *i*-th node in the *t*-th hour, V_n denotes the rated voltage, *r* denotes the resistance (Ω/km), *x* denotes reactance (Ω/km) and *l* denotes the length of the line (km).

The data for the weather forecast, the forecasted electricity consumption, as well as the prices for electricity trading, are input data in the algorithm. In order to be able to do the optimization, it is necessary to enter all the technical limitations, as well as the battery data, such as maximum charge ($P_{bat\_ch,\,max}$) and discharge ($P_{bat\_dis,\,max}$) and SOC. The algorithm analyzes the data in each interval (hour) and proposes an optimal solution based on the values of the parameters in the previous hour and the current situation. Then, the conditionally optimal solution is checked and if it satisfies the conditions, it is accepted, otherwise, a new solution is required. The flowchart of the proposed algorithm is shown in Figure 1.

It should be noted that if there is an outage in the system and the microgrid cannot provide the necessary power to meet consumption, the algorithm continues to work, so it finds the optimal solution in conditions when the microgrid operates in island mode. In that case, the operation of the diesel engine and the price of diesel fuel are considered.

IV. SIMULATION & RESULTS

The proposed method is applied to a microgrid composed of PV modules, wind generators, and batteries, simulated in Matlab. The microgrid trades with the local network, exchanging power under defined conditions. The analyzed microgrid is shown in Figure 2 and the installed power and the limitations under which the simulation is performed are shown in Table 1.

The analysis was performed on 24-hour data. The algorithm, taking into account the current weather conditions, battery charge, and electricity demand, performs an optimal unit commitment in the microgrid. If the obtained solutions are within the defined limits of the given constraints, the voltage in the nodes is checked. If the voltages are within the limits, of ±5% variation, the solution is accepted. Otherwise, the problem of optimization is reconsidered, until the obtained solution satisfies all the limitations.

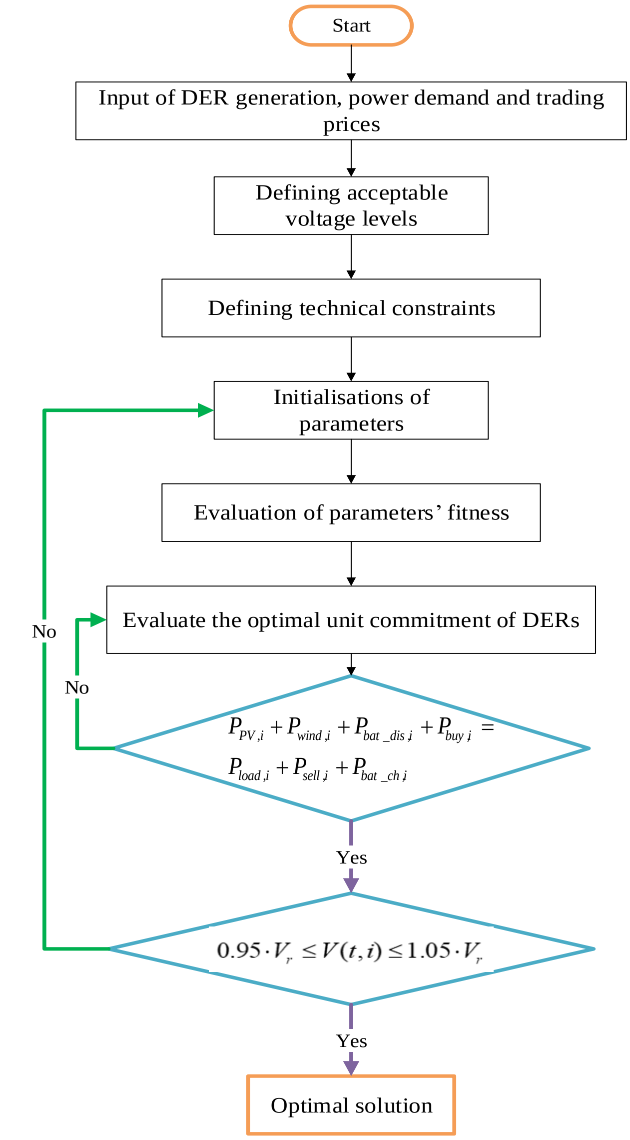

Fig. 1. Flowchart of the proposed algorithm

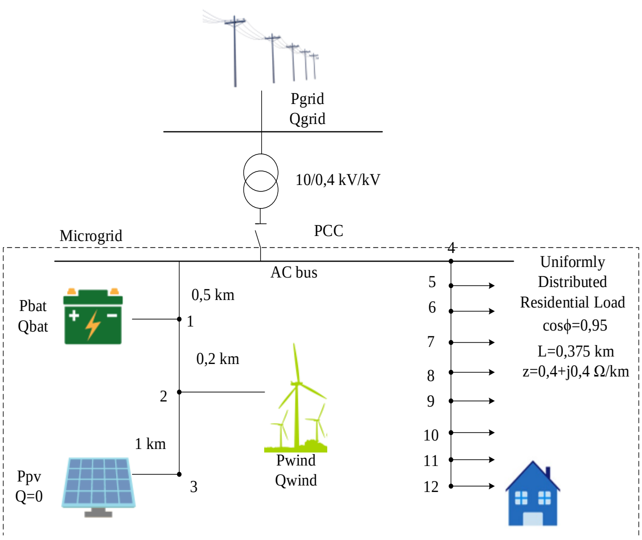

Fig. 2. Microgrid test example

Table II shows the prices for the power produced by PV and wind generators, the price for trading with the network, and storage in the battery.

The results of the optimization are shown in Figure 3. Figure 4 shows the optimal unit commitment in the microgrid. The total profit of the microgrid during one day is 12.56 €. This is a case of high RES production. If the weather conditions are unfavorable, production would be reduced, so the cost of buying electricity would be higher, which would reduce profits. Figure 4 shows the voltage variations in nodes 1, 2, 3, and 12.

TABLE 1. INSTALLED CAPACITY OF THE EQUIPMENT

Parameter	Meaning	Value	Unit
P_{PV}	PVs installed capacity	10	kW
P_{wind}	Wind generators installed capacity	12	kW
P_{bat_ch}	Maximum charging power of the battery	24	kW
P_{bat_dis}	Maximum discharging power of the battery	24	kW
P_{buy_max}	Maximum power bought from the grid	43	kW
P_{sell_max}	Maximum power sold to the grid	20	kW
SoC_{bat_min}	Minimal battery state of charge	48	kWh
SoC_{bat_max}	Maximal battery state of charge	240	kWh
η_{ch} η_{dis}	Efficiency coefficient of battery charging/ discharging	95	%
DoD	Depth of discharge	80	%

TABLE 2. ELECTRICITY PRICES

Unit	Notation	Price (€ct)
PVs	p_{PV}	16
Wind generators	p_{wind}	8.9
Bought from grid	p_{grid}	7,6
Battery	p_{bat}	0,3
Penalty costs	$c_{penalty}$	8
Reactive power from grid	c_q	7,5

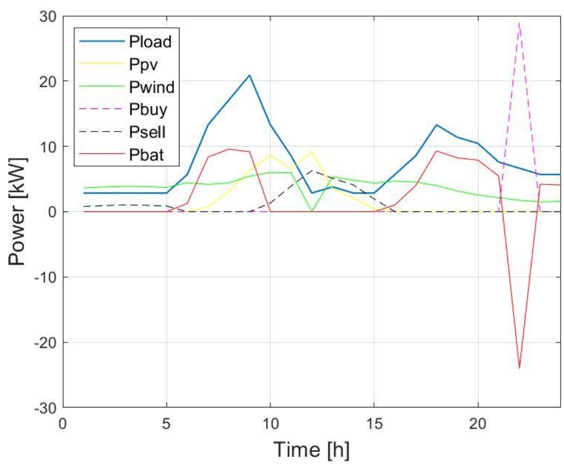

Fig. 3. Optimal power scheduling in the microgrid

The financial benefit of the analyzed microgrid under the same conditions, using a genetic algorithm, but without taking into account the voltage in the nodes is 12.48 €. In this case, due to the voltage variation, penalty costs are also charged, resulting in a 0.64% lower profit. The total benefit changes as the weather conditions and power demand change, and results in bigger earnings over a longer period of time.

The obtained results justify the proposed method and the need of taking into account the nodal voltages as part of the optimization process.

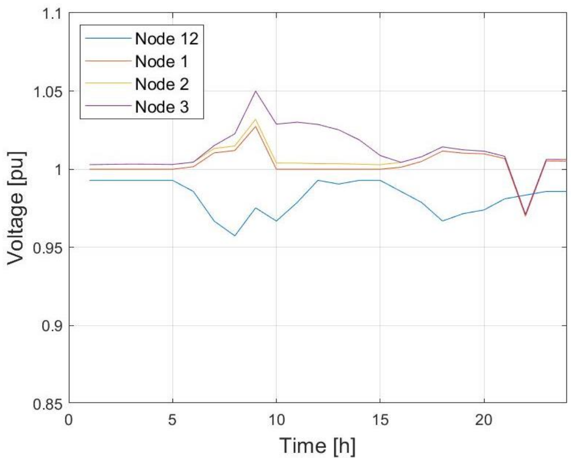

Fig. 4. Voltage variation in the nodes over 24 hours considering voltage regulations as part of the optimization process

V. Conclusion

Given the unreliability of the weather, no empirical or unified algorithm can solve the problem of microgrid optimization. This means that for their planning and optimization the edge mode is subjective and depends on the expectations of all stakeholders.

The method proposed in this paper is based on a well-known optimization technique and is most commonly used to solve this problem: the genetic algorithm. Its application aims at maximizing the financial profit from selling power to the utility grid, under certain technical limitations. During the optimization, the voltage in the nodes is taken into account, and emphasis is placed on its maintenance within defined limits that guarantee the stability of the network. Additionally, penalty costs are taken into account if poor quality electricity is supplied (voltage outside the defined limits) and if the power factor is not maintained at 0.95 or higher. Also, the reactive power supply from the utility grid is charged if it exceeds the defined amount.

The obtained results show the importance of voltage regulation in microgrids for providing a quality power supply. In future work, the proposed method will be applied and upgraded for analyzing the impact on the distribution network, considering multiple microgrid implementations, and the implementation of prosumers in the microgrids.

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