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UNIT COMMITMENT OF DISTRIBUTED ENERGY RESOURCES IN DISTRIBUTION NETWORKS USING THE DYNAMIC PROGRAMMING METHOD

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Abstract: The integration of renewable energy sources into the distribution networks improves the reliability of power supply, providing clean energy which does not cause pollution. However, the proper unit commitment of the available distributed energy resources helps to decrease the costs for their generation. This paper proposes a method for the unit commitment of RES without storage system based on dynamic programming. The method considers the costs for each RES power generated, depending on their availability at the moment.
Keywords: Dynamic programming, Renewable Energy Sources, Distributed Generation, Unit Commitment.

1. INTRODUCTION

Due to the decrease of fossil fuels based power plants usage, and the growing concern of sustainability, the renewable energy sources (RES) are receiving more attention and interest for investors and researchers. The number of RES constantly increases, as they have been successfully implemented into the standard power system in many countries. In that way, it has proven that the RES are quite beneficial both economically and environmentally, as they help in the pollution decrease and require lower maintenance costs [1][2]. However, their implementation into the big cities, which are facing air pollution, is still challenging, mainly due to the lack of space.

Distributed energy generation provides usage of small power plants which use RES as a source of power, by local consumers. These power plants are called distributed energy resources (DERs). They are usually with significantly smaller capacities than the fossil fuel power plants and often supported with back-up diesel generators or storage systems. But, since the storage systems are quite expensive, there are not usually any. In that case, during normal operation of the distribution network, the power generated from the DERs has to be used when it is available, and if there is an excess power it can be sold to the utility grid. The main benefit of the DERs is their ability for islanded work. That means that the local consumers can be supplied with power even if there is an outage in the distribution network.

As the technology of using the RES for power generation develops, the need for developing a method which optimizes the unit arrangement in the power network consisting of RES increases. The unit commitment problem in power system refers to the determination of units' power capacities to supply the forecasted load for a certain time. Therefore, optimisation methods are used, for generation arrangement with the lowest costs and highest reliability as criteria, while satisfying certain constraints. The constraints refer to the unit generation limit, load balance, allowed level of pollution, system reserves and customers' security [3].

In this paper, a method based on dynamic programming is proposed for the unit commitment of DERs connected to the distribution power network. The method analyses a cluster of DERs without a storage system. It takes into account the availability of each of the DERs, which depends on the power they can provide at the moment and the cost for generating power. The optimisation technique considers the constraints of the DERs regarding their power capacities limits. The case study analyses three different DERs including photovoltaic (PV) generator, wind power plant and run-of-river (ROR) hydropower plant. Each of the DERs has a certain power capacity.

2. RELATED WORK

DERs are one of the solutions to the environmental pollution problem. They produce electrical energy using RES, without emitting greenhouse gasses, and therefore they are a subject of interest to many researchers.

In [3] an optimisation method based on dynamic programming (DP) for optimal energy management in a hybrid system is proposed. The case study system consists of wind turbines, photovoltaic, diesel generator and a battery. The optimisation is based on minimising the costs by scheduling the DERs while taking into account the DERs limitations, emission reduction and balancing the load and production of electrical energy. The input data to the proposed method are the information of sources, loads, and electricity market. The optimisation considers the state of charge of the battery at any moment and that is the optimisation starting point.

A complex method for unit commitment problem in power system is proposed in [4]. The method is based on hybrid dynamic programming, genetic algorithm and particle swarm method. The analysis is made considering the available units and system security constraints. The simulation is made on complex power system consisting of hydro and thermal units on IEEE 30 buses system. The constraints include the dam reservoirs and the spinning reserves. The proposed method gives the optimal unit response, supplying customers economically.

A method based on a stochastic optimisation of microgrids is proposed in [5]. The method is used for an optimisation of the power generation in a local grid-connected microgrid with implemented storage system. The optimisation method considers the uncertainties regarding the microgrid optimisation, such as the load, which is assumed to be manageable, and the electricity market prices. The method has been simulated in Matlab, and the results have shown that considering the uncertainties delivers better results.

Unit commitment of microgrid power units is analysed in [6].The analysis is made based on a 24 hour ahead power planning of a microgrid with implemented storage system, micro gas turbines and active generators (such as PV arrays). For that purpose a DP method is used. The objective function considers the emissions from the power production units, especially CO_2 emissions and operating costs. The system constraints include the production and demand power balance, the unit's loading level and the microgrid operation mode. The results of method implementation are presented as a matrix containing the 24-hour ahead power production and the micro-gas turbine CO_2 emissions. The method determines the optimal unit commitment regarding the emissions from the micro gas turbines.

In [7] a dynamic programming method is used for determination of the optimal power capacities of four power plants, placed on different locations. Knowing the total power demand, the optimisation is made. The objective function is based on costs for building each of the power plants minimisations, depending on the power capacity installed.

3. DYNAMIC PROGRAMMING

Dynamic programming (DP) as an optimisation method was set by Bellman in the 1950s [8]. The method provides a solution to a certain issue by solving the smaller sub-issues. Although the method can be classified as a "divide and conquer" group of methods, it works opposite of them [8]. The optimisation is done by analysing the smaller issues first, and then the bigger ones.

DP is an optimisation method which provides a solution using a set of algorithms. It can be used for finding an optimal solution to a wide range of input data while maximising or minimising the objective function. The problem is divided into incremental steps, sub-problems, so that, at any step, the expressions are simplified. The method memorises the solutions, so eventually, the main solution follows the solutions to the sub-problems.

The DP method is used for solving many nonlinear problems. Its application is widely known for power system planning, optimal unit commitment in complex power systems, which cannot be solved by standard methods of nonlinear programming and energy management optimisation. Usually, the optimisation is done by minimising the costs or by maximising the benefits. However, in energy management optimisation, there are other parameters which are optimised, for instance, the level of pollution by greenhouse gasses, such as NO_x, CO_x, SO_x etc.

The optimisation is done by minimising or maximising, the following recursive relation [9]:

$$F_i(x) = \max\{F_{i-1}(y_i) + F_i(x - y_i)\} \tag{1}$$

where,

- *i* indicates the numeration of the sub-problems,
- *x* is the variable by which the optimisation is done, and
- *y* is the value corresponding to the analysed sub-problem.

The principle of DP is shown in Fig. 1. The solutions to the sub-problems are represented with circles, and the paths which connect the nodes are the possible state transitions. The optimal solution is the shortest path which connects the start and the end of the process (in Fig. 1 denoted as 1 and 19, respectively), and at the same time, satisfies some defined constraints. For instance, minimisation of costs or greenhouse gases emissions, maximisation of financial profit or availability of the resources.

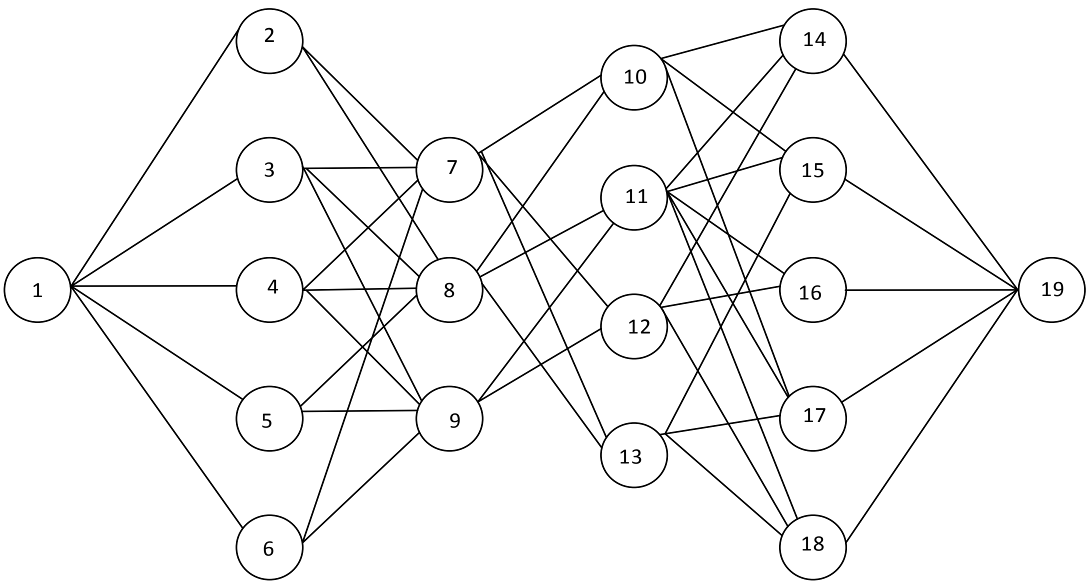

Fig. 1. Dynamic programming diagram

In this paper, the DP method is used for solving the unit commitment problem of a radial distribution network with implemented DERs. The analysed issue refers to an islanded operation of a complex distribution network when an outage occurs, cutting off the power supply to a certain cluster of consumers.

4. THE PROPOSED METHOD

The DERs' power generation depends on weather conditions. That means that if there is no storage system, the power generated has to be consumed at the time when it is available. However, the DERs do not produce maximum power at each moment, meaning that each DER produces a different amount of power at one moment. For instance, on rainy days, the ROR power plant will produce a higher amount of power, while PV will produce none.

The proposed dynamic programming-based method analyses the availability and power generation capability of the DERs installed and proposes an optimal unit commitment solution minimising the costs and analysing their availability for satisfying the power demand. The proposed optimisation algorithm, which is presented in Fig. 2, is done in the following manner:

1. Current weather conditions data input,
2. Unit generation limits for each DER,
3. Current power generation of each DER,
4. Calculation of the availability index of each of the implemented DERs,
5. Computation of the optimal DER's unit commitment.

Although the storage system provides more flexible power usage during outages and islanded work, it requires higher investment, which may be considered unproductive in some cases. Therefore, these power architectures are often supported by back-up diesel generators. Diesel generators provide power energy during outages for a limited time, which is defined in the designing process and mainly depends on the network architecture and power load.

In this paper, the availability defines a variable which depends on the weather condition index, the power capacity limit of the DER and the cost for power generation. The weather condition index represents the convenience of the weather conditions regarding the DERs' production and it is denoted as $W_i(P_i) \in [0,1]$. The weather condition index defines the availability of DERs and power production. The costs index for power production by DERs, denoted as $C_i(P_i) \in [0,1]$depend on the power capacity. The costs increase as power production increases. Then, the availability defines in the following manner:

$$A_i(P_i) = f(W_i(P_i), C_i(P_i)) \tag{2}$$

where,

- A represents the availability index of the DERs and it is a dimensionless quantity,
- i denotes the number of the DER, and
- P_i denotes the generated power.

The costs have to be minimised, and therefore the reciprocal value of the costs is considered.

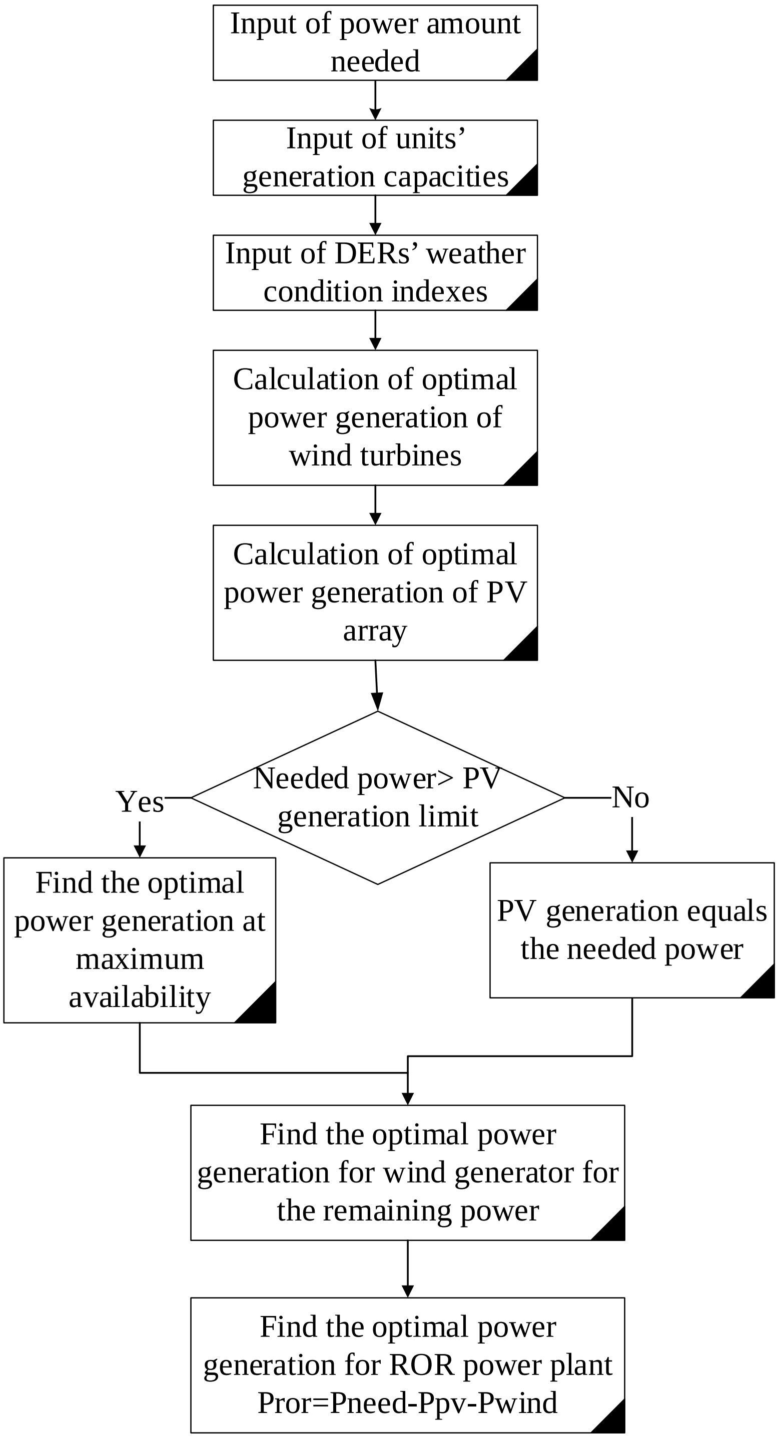

Fig. 2. The dynamic programming algorithm for solving the unit commitment problem

The power limits for each of the DER are different. The zero indexes indicate an absence of power in production, i.e. the weather conditions are not favourable. For instance, night hours are not favourable for PV generators as dry periods are for ROR power plants.

The objective function is defined as:

$$A_i = \sum_j A_j(P_j) \Rightarrow \max \tag{3}$$

where, j is the number of conditions of the DERs, and i is the number of DERs.

The optimisation equation represents a multi-step continuous process. In the first step, the power needed is set. Then, the optimal combination of available units is selected, using the following form of the recurring relation:

$$A_i^e(P_i^e) = \max\left\{A_i(P_i) + A_{i-1}^e\left(P_j - P_i\right)\right\} \tag{4}$$

where, P_i^e indicates the power needed in the *i*-th sub-problem.

The optimal combination is selected step-by-step, analysing all of the possible combinations and the power taken from each of the DERs, while minimising the costs. If the power that has to be supplied exceeds the power capability of the DERs at the moment, the optimal plan is done taking the maximum power produced by the DER with minimal costs, and the process continues until the power load is satisfied or all of the DERs are engaged.

5. CASE STUDY

The case study analyses a radial distribution network with connected DERs as shown in Fig 3. The system consists of industrial consumers and three DERs: a PV generator, a wind power plant and a ROR power plant. Additionally, there is a diesel generator connected to the low voltage bus, in case of insufficient power generation from the DERs. There are two power lines and two transformers with voltage rate 110/10 kV.

The first study case analyses a normal operation of a distribution network, meaning that there is no outage of the elements in the substation and DERs are producing maximum power. In that case, the consumers will use the locally generated power to the level that is accessible and profitable. The excess power will be generated into the utility grid.

The power limits for each of the DERs in the first case study are presented in Table 1. The availability of each DER is given with an index rating from 0 to 1. In the simulation, the availability rates of the DER were generated using a random number generator.

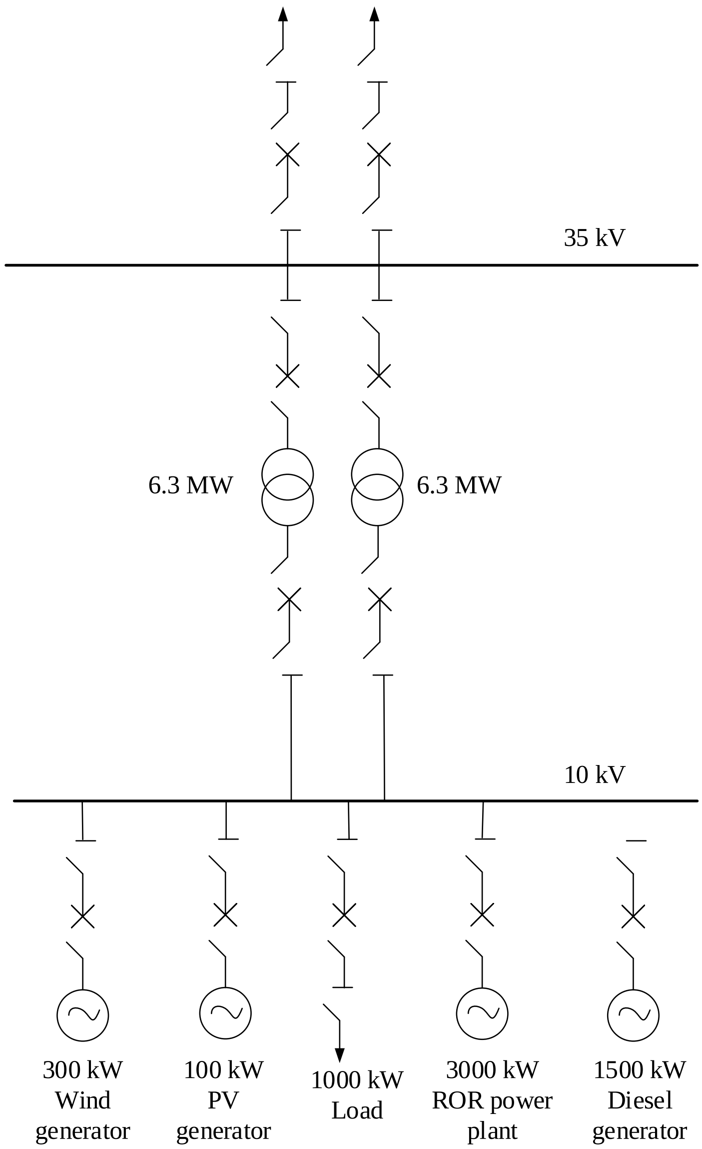

Fig 3. Distribution network with implemented DERs

Table 1 Power capacities of DERs

DER	Power capacity [kW]
PV	100
Wind	300
ROR	1000

As explained in [7], the dynamic programming optimisation is done step by step. In the first step no optimisation is done, and the data for the first DER is used. In this case, the data for the ROR power plant is used. That means that so far, only the ROR power plant will generate power. The algorithm optimises the system with a step of 1 kW (Table 2).

Table 2 Optimisation of ROR power plant

Power Capacity [kW]	1	2	3	…	2999	3000
ROR power plant availability (A_1)	0.8447	0.8828	0.9283	…	0.0926	0.4978

In the following step, the second DER is optimised, which in this paper, is the wind generator. In this step, the optimisation is done between the two DERs, ROR power plant and the wind generator. The calculations start with the power of 1 kW and continue until the power capacity limit of the wind generator is reached. The first calculation for the second DER is:

$$A_2(1) = \max\begin{cases} A_1(0) + A_2(1) = 0 + 0.1962 \\ A_1(1) + A_2(0) = 0.8447 + 0 \end{cases} \Rightarrow 0.8447 \tag{5}$$

In the next steps, the optimisation continues for the power of $2, 3, \ldots, P_{wind,generator}$, i.e. until the wind generator power limit is reached. The last optimisation equation, for the power of 300 kW power outage, is presented with the following expression:

$$A_2(300) = \max\begin{cases} A_1(0) + A_2(300) = 0 + 0.2430 \\ A_1(1) + A_2(299) = 0.8447 + 0.6156 \\ A_1(2) + A_2(298) = 0.8828 + 0.4266 \\ \vdots \\ A_1(299) + A_2(1) = 0.8227 + 0.1962 \\ A_1(300) + A_2(0) = 0.5250 + 0 \end{cases} = 1.9544 \tag{6}$$

The results of the optimisation are presented in Table 3

Table 3 Optimisation between the ROR power plant and the wind generator

Power Capacity [kW]	1	2	3	…	299	300
Wind generator availability (A_2)	0.1962	0.2154	0.4377	…	0.6156	0.2430
Conditionally optimal solution [kW]	0	1	1	…	128	269
Availability of the conditionally optimal solution	0.8447	1.0409	1.0790	…	1.8932	1.9544

As follows, the function is applied for the third DER, which is the PV generator. The optimisation is done between the PV generator and the optimised values of the wind generator and ROR power plant. The calculation is done until the power capacity limit of the PV is reached, which in this case is 100 kW. The conditionally optimised solution is presented in Table 4.

$$A_3(100) = \max \begin{cases} A_1(0) + A_2(100) = 0 + 0.2884 \\ A_1(1) + A_2(99) = 0.8447 + 0.5296 \\ A_1(2) + A_2(98) = 1.0409 + 0.9747 \\ \vdots \\ A_1(99) + A_2(1) = 1.6929 + 0.0793 \\ A_1(100) + A_2(0) = 1.8673 + 0 \end{cases} = 1.8918 \tag{7}$$

Table 4 Optimisation between the PV generator and the system

Power Capacity [kW]	1	2	3	…	99	100
PV generator availability (*A3*)	0.0793	0.6341	0.5515	…	0.5296	0.2884
Conditionally optimal solution [kW]	0	0	2	…	37	81
Availability of the conditionally optimal solution	0.6823	0.3298	1.2594	…	0.3210	1.8918

After the computation for all power rates is done, the calculation for the optimal unit commitment is made. First, the optimal power generation for the third DER is determined, according to the maximal availability. If there is no outage, and the distribution network is connected to the utility grid, and if the power that needs to be supplied exceeds the power capacity of the DER, the maximum power that can be provided, with maximum availability is considered. The remaining power that has to be provided is supplied by the two remaining DERs. The process continues until there is no power to be divided among the DERs. The solution gives information of the unit commitment regarding the power generation from all of the DERs.

In cases when there is no outage of the substation, and if the power generated from the DERs is not completely used by local load, the excess power is sold to the utility grid. The optimal solution of the analysed case study is given in Table 5.

Table 5 Unit commitment of the DERs

Distributed Generator	**Power generation[kW]**
PV generator	17
Wind generator	31
ROR power plant	952

The results show that only 17 kW will be used from total power generated from the PV generator, 31 kW power will be used from the wind generator, and 952 kW generated from the ROR power plant will be used by local consumers. The remaining power generated from the DERs will be sold to the utility grid.

Weather conditions change from one hour to another, and therefore at some another analysed moment, the unit commitment of the DERs will be different. An example of another optimal unit commitment is shown in Table 6.

Table 6 Change of unit commitment of DERs due to weather conditions change

Distributed Generator	Power generation capacity [kW]	Optimal power generation [kW]
PV generator	50	42
Wind generator	20	2
ROR power plant	2000	956

The second case study, analyses an islanded work of the reviewed distribution network. If there is an outage and the power supply from the power network is interrupted, the DERs need to provide power for the local consumers, at a maximum of 1000 kW. In that case, the DERs are loaded according to the power they produce and by the costs for its production. First, the DER that produces the highest amount of power, by minimum costs is loaded. If the locally generated power is not enough for satisfying the power need, the back-up generator is used. The diesel generator has to provide power for the load for at least 8 hours straight. Therefore, they are designed according to the peak power. The costs for diesel generator running depend on the diesel prices.

An example of the power generation from the DERs during an outage of the power substation is shown in Table 7. The power generated from the PV and wind generators may change hourly. However, the ROR power plant does not change its power generation with such high frequency. Therefore, along with the diesel generator, it can provide support to the local power network.

Table 7 Unit commitment of the DERs during islanded work

Distributed Generator	Power generation[kW]
PV generator	38
Wind generator	18
ROR power plant	394
Diesel generator	550

5. CONCLUSION

The implementation of DERs increases the clean energy production and provides higher reliability of power supply to the local consumers. In that way, a cluster of power generation facilities connected to the distribution network is formed. That means that in times of outages, the DERs can provide power for the local loads. Although the operation and maintenance costs of the DERs are relatively low compared to the standard power plants, they are present and the unit commitment of the DERs in the distribution networks has to be under minimal operation costs.

In this paper, the unit commitment problem was analysed, proposing a dynamic programming-based method for its solvation. The case analysis evaluates the unit generation from each DER regarding their constraints. The presented method responds to a real-life problem present in the contemporary smart grids. The method was developed in Matlab providing hour analysis if weather conditions are known. The presented results show that dynamic programming is an efficient mathematical tool for solving the unit commitment problem in complex networks with power generation that varies over time.

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