Application of the method of dynamic programming for solving the optimal unit commitment problem in distribution networks with local distributed generation

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Abstract. The continuous growth of communities leads to an increase in electrical energy usage. Besides the technological advance of power systems, still, there are outages which lead to an interruption in the power supply. The implementation of distributed generation provides usage of the local renewable energy sources for satisfying local power needs which in good manner complexes the distribution networks. However, because the distributed energy resources depend on the weather conditions, the islanded work is not quite reliable. Grid-connected distributed energy resources have enhanced power supply reliability. In this paper, a dynamic programming model is used for the optimisation of power generation by the local distributed energy resources. Assuming the distributed energy resources have storage systems, the model takes into account the battery charge at the moment and the availability of the distributed energy resources depending on the weather conditions and whether is day or night. It is assumed that the distributed energy resources have equal power capacities. Case study reviews a low voltage distribution network with plenty of distributed energy resources from different renewable energy sources implemented and a cluster of household consumers.

1. Introduction
As renewable energy sources (RES) take a big swing in the power production process, they become easily implemented into the standard power system. In the past decade, they have become quite accessible for commercial use, not just as power plants, but also as a distributed generation. In that way, their implementation is very useful, especially in the isolated distribution networks, where the outages are very common or the electrical grid cannot be upgraded according to the increase of consumption. In such a manner, they provide electrical energy to the local consumers, which manifests with many benefits. One of the beneficial uses of distributed energy resources (DERs) is the opportunity they provide for islanded work. That means that when there is an outage of power lines or in the local substation, the consumers will not be left without power supply.

However, DERs highly depend on the weather conditions, which make them quite unreliable for islanded work only. With storage systems included, they can store the excess power, that can be used whenever needed or it can be sold to the power system when the price for selling it is acceptable. Studies have shown that implementation of storage systems increase the price of DERs, but their
purpose justifies the investment made as many communities today have implemented DERs in the local distribution networks.

Distribution networks with implemented DG, work similarly as the standard power system when it comes to optimal DG usage, especially during islanded work. The proper scheduling of the available DERs will provide optimal power usage while decreasing the expenses used for power production and storage.

In this paper, the optimal DERs unit commitment is analysed, considering the availability of the DERs implemented in the local network. For that purpose dynamic programming (DP) is used. The presented approach provides a solution for optimal usage of the local DG, considering their availability in a certain moment, based on the information about weather conditions and battery charge of each of the DERs. Their availability is presented with an availability index, which is a number between 0 and 1. DP method is supposed to give the optimal unit commitment of the DERs available.

2. Related work
DG as one of the solutions to the technical and environmental problems of power supply in modern communities is subject of interest to many research. In this section researches referring to the implementation of DP for resolving the problem with DERs unit commitment are reviewed.

In [1] an optimisation method for optimal energy management in a hybrid system is proposed. The system consists of wind turbines, photovoltaic, diesel generator and a battery. The optimisation is based on minimising the costs by scheduling the DG while taking into account the DERs power generation limitations, emission of greenhouse gases reduction, balancing the load and production of electrical energy.

In [2] a hybrid DP, genetic algorithm and particle swarm method for optimisation of power systems and unit commitment problem solution is proposed. The analysis made considers system security constraints. The simulation is made on complex power system consisting of hydro and thermal units on IEEE 30 buses system. The proposed method has shown to be quite effective.

In [3] a method for stochastic optimisation is proposed. The method is used for optimisation of power generation in a local grid-connected microgrid with an implemented storage system. The optimisation is made considering the load, which is assumed to be manageable, and the electricity market prices. The simulation on a typical microgrid shows that the proposed method delivers better results when the scheduling uncertainties are taken into consideration.

In [4] an analysis of a microgrid with implemented storage systems is made using DP. The objective function is minimising the emissions from the power production units, especially CO₂ emissions. The constraints are referring to the production and demand power balance, the unit’s loading level and the microgrid operation mode. The constraints are different for each mode of operation, and it depends on whether is day or night, the availability of RES and the battery state of charge. The simulation results show that the approach is applicable and effective, providing lower CO₂ emissions, compared to the systems that are not optimised in this manner.

In [4] a DP method is used for computation of the optimal power capacities of four power plants, placed on different locations, if the total power capacity is known. The optimisation is based on decreasing the costs for building each of the power plants, depending on the power capacity installed.

The proposed approach in this paper is based on the DP method used in [4], but it is used for optimal unit commitment in a power network with DERs installed.

3. Dynamic Programming Method
The application of DP is widely known for power system planning and optimal unit commitment in complex power systems. In this paper, DP is shown to be useful for optimal unit commitment in a distribution network with multiple DERs connected.

Usually, the conventional use of DP analyses the costs for running a certain unit, so the optimal unit commitment is based on minimal costs. In this paper, the optimal unit commitment in a complex
distribution network with multiple DERs is based on finding the optimal solution depending on the current availability of the DERs.

DP method represents a set of algorithms used for finding an optimal solution to a wide range of input data while maximising or minimising an objective function. The problem is divided into incremental steps, so that, at any step, the expressions are simplified. They are known as sub-problems. The solution to the previous sub-problem is memorised, so eventually, each of the solutions to sub-problems leads to the solution of the main problem.

Presented on a diagram, the solutions are represented with circles, and the paths are the state transitions. An optimal solution is a path which connects the start and the end of the process (in Figure 1 denoted as 1 and 19, respectively), and at the same time, satisfies some defined conditions.

4. Distributed Generation problem definition
The implementation of DG into the distribution network has been proven to enhance the power network reliability, especially in cases of an outage of the power lines or even outages in equipment in the substations. Their primary purpose is to serve the local consumers, providing with clean energy in times of power supply interruptions from the main power grid, as shown in Figure 2. However, due to their dependability on weather conditions, they cannot be used as stand-alone systems. Therefore, the preferable solution for the DG is to be grid-connected.

An islanded local distribution network unit commitment can be analysed as a power system with many different units. When analysing a large power system, the optimisation function is based on the costs for unit power generation. However, in the case of DERs, the main problem is their availability, considering that they are mainly RES.

In this paper, the problem with unit commitment is analysed based on units’ availability at the time, taking into account the weather conditions.
5. Proposed approach

The problem definition refers to determining which units should be used in a certain moment for power consumption satisfaction, assuming there is an outage, if known the availability of each unit and their power limitations.

The developed algorithm consists of the following stages:

- Current weather conditions data input,
- Current storage data input,
- Calculation of the availability index of each of the implemented DERs,
- Calculation of the DER’s power production if there is no energy stored for further usage,
- Computation of the optimal DER’s unit commitment.

The power generated from the DERs depends on the availability of the proper weather condition (sun, wind etc.). Applying storage systems provides power storage, in cases when the DERs produce excess power, so it can be used in the future, when there are no proper weather conditions or during night time. Therefore, the power generated from the DERs can be defined by weather conditions and the capacities of the storage systems.

In this paper, the availability \( A_i(P_t) \) is defined as a variable depending on the weather condition index and the capacity and availability of the power stored. The weather condition index denotes as \( W(P) \in [0,10] \), and the capability of operation and stored energy denotes as \( C_i \in [1,10] \). The availability function depends on the presence of the renewable energy source at the moment and the stored energy:

\[
A_i = aW_i(P_t) + (1 - a)C_i
\]  

(1)

where, \( \alpha \) represents the index of importance, which is a subjective decision depending on the one that is applying the proposed approach. The functions of weather conditions depend on the RES used for power generation, and it differs for each DER. For instance, the power generated from the photovoltaic power plant (PV) is not calculated in the same way as the power generated from wind farms.

The zero indexes represent the state of absolute absence of energy. It may occur, for instance, during the night time, when the sunlight is absent, if there is a solar power plant, or if there is a wind farm, the absence of wind. However, it will not be such case if there is a small hydropower plant, or a biogas power plant. Regarding the capability of operation and stored energy, the battery cannot be completely drained, because of the depth of charge limits, and therefore the values for the indexes start from one. The objective function is defined in the following manner:

\[
A_j = \sum_i A_i(P_t) \Rightarrow \text{max}
\]  

(2)

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

The optimisation equation is set up as a multi-step continuous process. First, the power needed is set as a goal. Then, the optimal combination of all the available DERs is done, using the following equation, which takes the form of a recurring relation:

\[
A_i^e(P_t) = \max \left\{ A_i(P_t) + A_{i-1}^e(P_j - P_i) \right\}
\]  

(3)

The optimal combination is done step-by-step, analysing all of the possible combinations and the power taken from each of the DERs.

6. Case study

The case analysis reviews two different substation configurations with connected distributed generation. The case study analyses a radial distribution network as shown in Figure 3. The system consists of three consumers and five DERs. There are two power lines and the substation voltage rate is 10/0.4 kV/kV. In Table 1 the availability of each the DERs for different power is presented.
Figure 3. Distribution network with implemented DERs

Table 1 DERs power capacities and their availability

| DERs power capacities [kW] | 50 | 100 | 150 | 200 | 250 |
|---------------------------|----|-----|-----|-----|-----|
| DER_1                     | 2.3| 1.6 | 5.4 | 1.8 | 2.3 |
| DER_2                     | 3.5| 6.4 | 2.9 | 3.6 | 3.5 |
| DER_3                     | 8.2| 7.3 | 7.4 | 6.2 | 8.2 |
| DER_4                     | 1.5| 6.4 | 1.8 | 7.8 | 1.5 |
| DER_5                     | 4.3| 4.5 | 6.8 | 8.1 | 4.3 |

Assuming that 500 kW have to be supplied from the DG at one moment in time, due to an outage in the power lines, the optimal solution calculated using DP is presented in the following. Another assumption made, due to simpler analysis, is that the power generation step is 50 kW.

Following the explanation for applying DP for power system optimisation in [4], in the first step, no optimisation is done, and the data for DER_1 is used. That means that so far, only the first DER will generate power.

In the next steps, the rest of the DERs are loaded. The optimal unit commitment analysis is done as shown with eq. (4). The example refers to a 100 kW power outage, for DER_2:

\[
A_2(0) + A_1(100) = 1.6
\]

\[
A_2(100) = \max \begin{cases} A_2(50) + A_1(50) = 3.5 + 2.3 = 5.8 \Rightarrow 5.8 \text{ (at the power of 50 MW)} (4) \\ A_2(100) + A_1(0) = 6.4 \end{cases}
\]

Then, the function is applied for power of 150 kW, then for 200 kW etc. Then, it continues for the following DERs. The eq. (5) refers to the third DER and the power of 350 kW. This process continues to the desired power of 500 kW. The optimisation is done five times, since there are five DGs. The eq. (6) refers to the fifth DER and the power of 500 kW.

\[
A_3(350) = \max \begin{cases} A_3(0) + A_2(350) = 9 \\ A_3(50) + A_2(300) = 8.2 + 8.3 = 16.5 \\ A_3(100) + A_2(250) = 7.8 + 11.8 = 19.1 \Rightarrow 19.1 \text{ (power of 100 MW)} (5) \\ A_3(150) + A_2(200) = 7.4 + 8.9 = 16.3 \\ A_3(200) + A_2(150) = 6.2 + 8.7 = 14.9 \\ A_3(250) + A_2(100) = 8.2 + 6.4 = 14.6 \end{cases}
\]
After the computation is done, the unit commitment process starts. First, the optimal power generation for the fifth DER is determined. In this case, it is the power of 150 kW. Then, the remaining power is transferred to the forth DER, and the process continues until there is no power to be divided among the DERs. The solution gives the information of unit commitment regarding the power injection from all of the DGs.

The information from the results containing the highest availability and the optimal generation for each unit is stored and used in further calculations. The optimal solution to the analysed case is given in Table 2:

| Distributed Generator | Power generation[kW] |
|-----------------------|-----------------------|
| DER₁                  | 0                     |
| DER₂                  | 100                   |
| DER₃                  | 50                    |
| DER₄                  | 200                   |
| DER₅                  | 150                   |

The results show that the DER₁ will not be used at that certain moment for a 500 kW power supply.

7. Conclusion
This paper analyses the application of DP for optimal unit commitment in a distributive network with implemented DG. The case study reviewed a distributive network consisting of five DERs connected to different locations in the network, each with the capability of providing up to 250 kW, and a storage system installed. The availability took into consideration the probability of RES power generation and the availability of stored energy. For simpler analysis, a step of 50 kW was considered.

Although the application of DP for solving the unit commitment problem in complex power systems is widely known, in this paper it was shown that it can be applicable for particular part of the power network with local power distribution.

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