Continuity of power supply in smart grid with PV penetration

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***Abstract* — The construction of new distribution infrastructure and the reconstruction of the existing one is associated with huge investment costs. These costs further increase from the penetration of many new RES, which are in most cases directly connected to electricity grid without considering the nature of the load profile of consumers in accession branch. The operational independence of the Distribution companies allows them to combine, in an appropriate manner, electricity producers and domestic and industrial users. This way, the electricity distribution company is directly able to influence the indicators of continuity of electricity supply. Taking into consideration the above, the article analyzes the various configurations of the traditional passive distribution network with and without PV PPs, active distribution network with and without PV PPs. This article proposes an optimization solution with differently oriented PV PPs, which improves the indicators of continuous power - SAIDI, SAIFI and helps to reduce electricity losses and the time to overcome the emergency situations.**

Keywords— Smart grid; PV; SAIDI; SAIFI; power distribution reliability; distribution network; load profile; demand response.

I. INTRODUCTION

The reliability of electricity supply is a key indicator for electricity distribution companies and to the greatest extent can limit the customer satisfaction of the service provided by the DSO [1], [2], [3], [4], [5]. The continuous increase of the new needs [6], [7] combined on one hand, with the aging facilities and the tougher competition from another hand - more stringent regulations in the power system, is one of the reasons that forced the DSO (Distribution System Operator) to focus investments on equipment and reconstruction of distribution facilities. The aim is at reducing the number and duration of interruptions.

The new market participants (the electricity generators connected to the distribution network are constantly increasing) and the new requirements impose the need for modernization of the conventional, passive distribution network [8]. The traditional approach of designing electrical networks, by following the vertical integration is well known.

However, to the traditional - passive electrical network are connected mainly electricity consumers. The new requirements, proposed by the EC related to the construction of new capacities from renewables and the emerging prospects for their intensive growth in the coming years, require DSO to design the electrical network in a way that takes into account the impact of new entrants in terms of the impact they have on the reliability of electricity supply.

The modeling of the distribution network demands the use of the following components: Feeders of distribution systems deliver power from distribution substations to customers. A feeder normally begins with a feeder breaker at the substation point, and the main components of a feeder include lines, poles, a breaker, switches and fuses, transformers, and capacitors and generators.

PV PPs (Photovoltaic Power Plants) are one of the RES generators, which, if properly designed, depending on the load and the orientation can reach a maximum working capacity, depending on the type of the load. If the predominant load for example, is from 8-12 hrs, most appropriate orientation of the PV PPs is to face east, if it is from 10-14 hrs., then it faces south and if from 14-18h. – west, etc. It is absolutely possible to build PV PPs, where the panels have a different orientation, in order to ensure an optimal coverage of the load. Taking into consideration this fact, and in relation with the consumer needs, one of the measures that could be undertaken are linked with the automation of switches and fuses, relay protection, systems for predicting failures, and upgrade the grid. This approach has been provoked by the understanding that the active network is the one that is automated and that allows to regulate the load profiles of consumers and of electricity generators.

In this sense, one of the major issues that remains to be solved by the distribution companies is to substitute the traditional passive electricity networks with active electricity networks as a necessary precondition of building a smart grid, to increase the number and the capacity of the newly connected RES (PV PPs), to increase the reliability, and all this to happen with minimum investment costs. Solving this optimization task requires, by a simulation of the double feed distribution network with or without automation of PV PPs, to assess the influence of the differently oriented /east, south, west/ PV PPs for increasing the reliability of the distribution network. By using economic and technical indicators, the investment costs and the technical SAIDI and SAIFI are assessed. The goal is to improve the reliability of the distribution network by decreasing the SAIDI and SAIFI indexes [9]. The value of the SAIDI indicator can be optimized by decreasing the number of continues interruptions and/or by decreasing their duration.

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One of the practically acceptable approaches to improve SAIFI is to decrease the number of the long electricity interruptions.

The expected benefits for the distribution companies, a result of the development of absolutely new model for design of distribution networks, can be summarized as follows:

- Increase of the reliability, security and sustainability of the energy system;
- Diversification of the electricity supply; decrease of the carbon emissions;
- Optimization of the investment costs;
- Acceleration of the processes linked to establishing a new strategy for development of the energy system.

II. ALLOCATION OF PV PPS IN MEDIUM VOLTAGE GRID

A. Simulation

The effective planning and management of the processes linked to: the penetration of decentralized renewable energy sources in the EES, the change of the structure of the electricity consumed, the rehabilitation, modernization and construction of new facilities requires a new generation computer models. SPREAD [1]helps optimizing a variety of technical solutions that minimize: the capital costs; electricity losses, maintenance and exploitation costs. The optimization process goes along with some technical limitations like voltage profile, maximum distribution capacity of the facilities, quality of the services offered, minimum losses, minimum interruptions and others. The computer model offers many solutions and allows a network optimization of: conventional generators and generators with RES;

- Optimal network expansion;
- Network reconfiguration;
- Quality of the offered services;
- Optimal allocation of DES;
- Decrease of losses;
- Improvement of the sustainability;
- Risk assessment.

On this basis it is possible to reconfigure the Medium Voltage (MV) grid by reducing the investment costs and increasing the quality of services offered.

B. Input data

The technical data for an existing MV network Figure 1, that is to be optimized with a connection of a RES, are introduced. The technical characteristics of the electrical network and the generating source are used. The existing MV network is examined, Figure 1 and Table I, with 23 nodes, which is supplied by two substations. The data for the substation and nodes are summarized in Table I. The data for the load pattern have an interval of 1 hour and are presented on Figure 2.

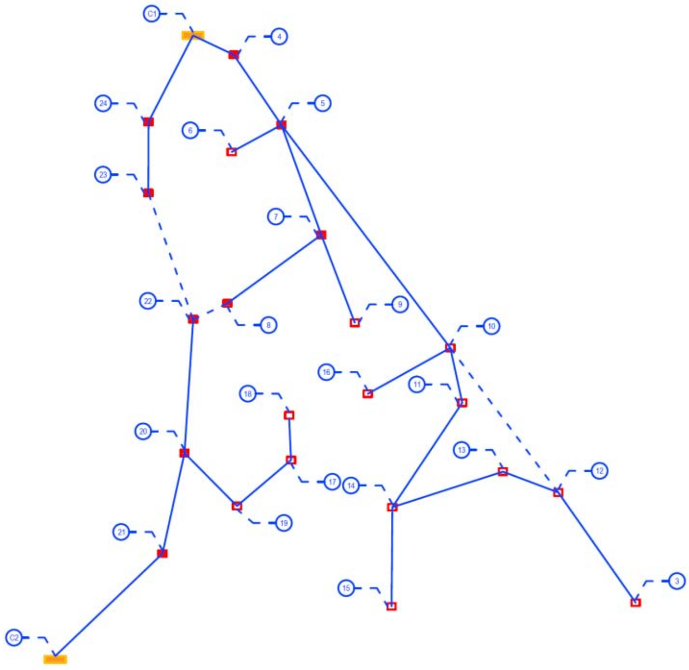

Fig. 1. Existing MV grid

The implementation of active distribution network that involves controllable loads, generators and storage devices, may reduce the negative impact of RES on the distribution systems avoiding or deffering major system investments. The planning of the distribution system is strongly influenced by the introduced level of active management.

TABLE I.

From node № to node №	Distance, km	Type Overhead line, cable line	mm^2	Current, A
1-4	0,864	Cable line	240	360
4-5	1,52	Cable line	240	360
5-6	1,003	Cable line	95	200
5-7	2,105	Cable line	95	200
5-10	5	Cable line	95	200
7-8	2,051	Cable line	95	200
22-23	2,398	Cable line	240	360
23-24	1,302	Cable line	240	360
22-8	0,668	Cable line	95	200
1-24	1,846	Cable line	240	360
7-9	1,692	Overhead line	16	105
10-11	1,024	Overhead line	16	105
10-16	1,658	Overhead line	16	105
11-14	2,243	Overhead line	16	105
14-15	2,181	Overhead line	16	105
14-13	2,046	Overhead line	16	105
13-12	1,045	Overhead line	16	105

[1] SPREAD is a software package, developed by RSE, for the optimal planning of MV distribution network in presence of ADN (Active Distribution Networks)

3-12	3,24	Overhead line	16	105
10-12	2,419	Overhead line	16	105
17-18	0,804	Overhead line	16	105
17-19	1,257	Overhead line	16	105
19-20	1,325	Overhead line	16	105
20-21	1,86	Overhead line	35	190
2-21	2,788	Overhead line	35	190
20-22	1,215	Overhead line	35	190

a. Technical characteristics of the analyzed MV network

The loads used are according to the area of consumption. The urban loads are in urbanized territories, the agricultural – in areas where there are active agricultural companies and in small towns and villages. The industrial loads are in the areas characterized by strong industry and many administrative buildings.

The software SPREAD allows identifying an optimal configuration (topology, conductor section, location and number of automatic and sides of backup feed) at minimal cost. The algorithms for the search of optimal configurations are based on Genetic Algorithms

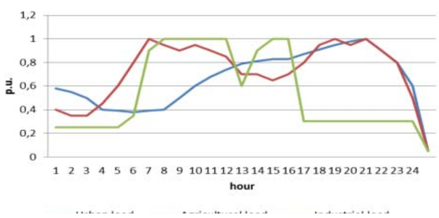

Fig. 2. Loads during simulation

The distribution network supplies electricity to the all three kind of consumers. The approach is to take in to account the most sophisticated situation when each type of consumer has different characteristics. In other studies as [9] the authors consider to apply their methodology on separate areas of services in order to find whether the incentives for continuity of supply should be the same or not depending from the area of customer which is served. In a lot of countries the type of customers are not clearly defined, in such case it is more useful to use combined load curves.

III. Results

This section presents the main results of the simulations of passive and active distribution networks with and without connected to the electricity grid PV PP with south orientation as well as PPP oriented east / south / west. An assessment of unsupplied energy and duration of the accident for each node of the studied network is done.

A. Passive and active distribution networks with and without connected to them PV PPs

The first option provides:

- To be simulated passive and active distribution networks without any generating sources;
- To be assessed the amount of unsupplied energy and duration of the interruption.

In electrical networks without dispersed generators electrical current is unidirectional from centralized generating sources to consumers. Analyzed passive distribution network does not allow managing electrical loads. Active distribution network allows electrical loads to be adjusted in the range from 0% to 100%. To both distribution networks there are no generating sources. Energy flow remains unidirectional.

TABLE II.

Node	**Passive MV grid without PV PPs**		**Active MV grid without PV PPs**	
	Unsupplied energy [kWh]	***Duration of interruption [min]***	***Unsupplied energy [kWh]***	***Duration of interruption [min]***
3	2150,18	312	2150,8	312
4	0	0	0	0
5	0	0	0	0
6	466,37	14	466,37	14
7	0	0	0	0
8	0	0	0	0
9	756,48	60	756,48	60
10	1564,82	72	1564,82	72
11	1348,24	195	1348,24	195
12	2696,49	195	2696,49	195
13	3505,44	195	3505,44	195
14	2696,49	195	2696,49	195
15	7553,93	274	7553,93	274
16	3896,21	131	3896,21	131
17	1324,72	96	1312,68	95
18	4738,33	125	4705,22	124
19	1053	51	1034,94	50
20	15,96	3	0	0
21	0	0	195,72	3
22	0	0	0	0
23	105,38	0	0	0
24	105,38	0	0	0

b. Technical characteristics of the analyzed MV grid with/without PV PP

Simulation data shows Table II, that in passive distribution network without PV PPs, the unsupplied electrical energy is 33977,42 kWh, for a total duration of failures of 1918 min. Within the active distribution network without PV PPs, the unsupplied energy is 33883,83 kWh, for a total duration of failures of 1915 min. The difference in the total quantity of unsupplied energy and duration of incidents is low. A more significant effect may be sought in the change of the locations of accidents, i.e. in a passive distribution network failures are in 18 nodes, while in active distribution network in 16 nodes.

B. Passive and active distribution network with south oriented PV PPs

Under the second option, the passive distribution network does not allow to manage electrical loads / the connected PV PPs traditionally are oriented on the south, and cannot be regulated/. The active distribution network allows electrical loads and generation sources to be adjusted in the range from 0% to 100%. The total installed capacity of PV PPs in different nodes of the distribution network is 13,5 MWp.

TABLE III.

Node	Passive MV grid with south oriented PV PPs		Active MV grid with south oriented PV PPs	
	Unsupplied energy [kWh]	***Duration of interruption [min]***	***Unsupplied energy [kWh]***	***Duration of interruption [min]***
3	2150,8	312	2150,8	312
4	0	0	0	0
5	0	0	0	0
6	466,37	14	466,37	14
7	0	0	0	0
8	0	0	0	0
9	756,48	60	756,48	60
10	1564,82	72	1564,82	72
11	1348,24	195	1348,24	195
12	2696,49	195	2696,49	195
13	3505,44	195	3505,44	195
14	2696,49	195	2696,49	195
15	7553,93	274	7553,93	274
16	3896,21	131	3896,21	131
17	1324,72	96	1312,68	95
18	4738,33	125	4705,22	124
19	1053	51	1034,94	50
20	15,96	3	0	0
21	0	0	195,72	3
22	0	0	0	0
23	105,38	0	0	0
24	105,38	0	0	0

c. Technical characteristics of the analyzed MV grid with south oriented PV PP

The analysis of the technical characteristics of the analyzed MV network Table III shows that results are very similar to those from option one, in passive distribution network with PV PPs, the unsupplied energy is 33978,04 kWh, for a total duration of failures of 1918 min. Within the active grid with the PV PPs, the unsupplied energy is 33883,83 kWh, for a total duration of interruptions of 1915 min. The distribution of accidents is in 18 nodes for passive and 16 nodes for active distribution network. The positive effect in the analyzed option can be found in decentralization of power system and reduce carbon emissions.

C. Passive and active distribution network with PV PP oriented east / south / west

When constructing PV PPs, the panels are usually oriented to the south. According to a study [11], the amount of electricity produced by PV PPs with an orientation and e/s/w is approximately the same as the orientation of the PV PPs with just to the south orientation. The advantage in this orientation is that it allows connection to the distribution network of more PV PPs.

The purpose of the third option is to assess the impact of this type of PV PPs orientation (east/south/west) over the unsupplied energy and duration of interruptions as indicators of power quality.

In the research option passive distribution network does not allow the electrical loads to be managed. To it are connected PV PPs e/s/w, which also could not be managed. In the same time the active distribution network allows electrical loads and generation sources to be adjusted in the range from 0% to 100%.

TABLE IV.

Node	Passive MV grid with e/s/w oriented PV PPs		Active MV grid with e/s/w oriented PV PPs	
	Unsupplied energy [kWh]	***Duration of interruption [min]***	***Unsupplied energy [kWh]***	***Duration of interruption [min]***
3	802,56	116	802,56	116
4	0	0	0	0
5	0	0	0	0
6	466,37	14	466,37	14
7	0	0	0	0
8	0	0	0	0
9	756,48	60	756,48	60
10	0	0	0	0
11	555,6	80	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	180,78	6	0	0
16	1765,97	59	1765,97	59
17	1279,14	92	1279,14	92
18	2675,01	70	2675,01	70
19	984,62	47	984,62	47
20	0	0	0	0
21	384,15	6	0	0
22	0	0	0	0
23	0	0	0	0
24	0	0	0	0

d. Technical characteristics of the analyzed MV grid with e/s/w oriented PV PP

In this case Table IV, in contrast to the results presented in section 3.1 and 3.2 for the passive distribution network with connected photovoltaic power plants located e/s/w, the unsupplied energy is reduced to 9850,68 kWh. The time for interruptions is also less the total duration is 550 min. In the active distribution network and the same PV PPs, the unsupplied energy is even lower - 8730,15 kWh and the total duration of interruptions is 458 min. The accidents are reduced to 10 nodes in passive and 7 nodes in active distribution network. In addition, the total number of PV PPs is 16,5 MWp, in both networks with differently oriented PV PPs, which is an additional advantage in decentralization of power system and reduction of the amount of carbon emissions.

At this stage of the study for distribution companies the most appropriate is the variation of the active distribution network with photovoltaic power plants located e/s/w. The next stage considers what investment costs are required for different options.

D. Costs for distribution network

In practice, in addition to the role of passive and active networking with PV PPs and their impact on the amount of undelivered energy and duration of the interruptions, a key factor for the implementation of one or another technical solution is the size of the investment cost. Table V summarizes the investment costs necessary to implement the simulated patterns. Calculations were made taking into account the capital expenditure /CAPEX/ and ongoing operating costs/ OPEX/.

TABLE V.

Investment costs for distribution network	
Type of network	***1000/EUR***
PV PP e/s/w - passive	969,57
PV PP e/s/w - active	849,89
Passive network without PV PP	1246,18
Active network without PV PP	823,98
Passive network with PV PP	1167,37
Active network with PV PP	712,83

e. Investment costs for distribution network

The investment costs Table V, for constructing a distribution network using a traditional model are the greatest - around 1246.18 thousand. As currently this is the traditional way of investing in the grid, we take it as a basis. The other options can be arranged in the following manner:

1) The lowest investment costs are achieved with active network with south oriented PV PPs. This network is expected to be 74.82% less expensive than the traditional passive network. The total installed capacity of PV PPs is 13,5 MWp;

2) When constructing an active network without RES, the investment costs are 51.24% lower compared to the costs of construction of a traditional distribution network;

3) The active distribution network with 16,5 MWp photovoltaic power plants with different orientation is 46.63% cheaper than the traditional network. The difference compared with option 2 is 4.61%, but at the same time the penetration of PV PPs are with 22.22% more;

4) The passive distribution network with 16,5 MWp photovoltaic power plants with different orientation is 28.53% cheaper than the traditional network;

5) If the network is passive, but is with connected photovoltaic power plants with a total installed capacity of 13,5 MWp, it is 6.75% less expensive than the traditional;

In the evaluation phase of the investment cost, the best investment decision for electricity distribution companies is building an active network with south oriented PV PPs. In order to make a comprehensive assessment should be checked and how to modify the parameters for power quality at the alternative scenarios for investment decisions.

E. Indicators for continuity of power supply

As any commercial company DSO are also looking for better return on investment. In order to keep the quality of the services provide there are price regulations which depends from the quality of supply. This is one of the reasons why the Council of European Energy Regulators (CEER) periodically surveys and analyses the quality of electricity supply in its member countries[11]. All countries have used different indicators but two of the indicators are common for all SAIDI and SAIFI [12].

SAIDI measures the average number of minutes an average customer was without power during a year. SAIFI measures the number of sustained outages the average customer has experienced over a specific period of time. Interruptions greater than five minutes are the only interruptions included in the SAIFI calculation.

The indicators that are used for reporting the continuity of power supply are:

- The System Average Interruption Frequency Index is the most commonly used indicator reported average number of interruptions per consumer for a period of one year. It is calculated with the aid of the following equation:

$$SAIFI = \frac{\sum_{i=1}^{m}(n_1 + \cdots + n_i + \cdots + n_m)}{N}, \frac{pcs}{year} \quad (1)$$

where:

n_i – number of customers affected by *i* interruption;

N – total number of connected consumers;

m – numbers of interruptions.

- The System Average Interruption Duration Index (SAIDI). This indicator takes into account the average duration of interruptions for a single user for a period of one year (in minutes per year). It is defined as the ratio of the sum of the duration of interruptions of the total number of users to total users. It is calculated using the following equation:

$$SAIDI = \frac{\sum_{i=1}^{m}(t_1 n_1 + \cdots + t_i n_i + \cdots + t_m n_m)}{N}, min \quad (2)$$

where,

n_i – number of customer affected by *i* interruption;

ti – the duration of *i* interruption;

N – total number of connected consumers;

m – numbers of interruptions.

The simulation of medium voltage network with SPREAD and analysis of the simulation results in the cases studied Table VI, indicating that the active network has a better results for SAIDI compared to the passive network. Moreover, the active network allows greater penetration of photovoltaic power plants, which is a prerequisite for accelerating the processes related to decentralization of the energy system. A positive effect can be further increased by increasing the degree of automation. In the studied cases only generating sources and loads are automated.

TABLE VI.

Indicators for continuity of power supply				
Type of network	**SAIDI**	**node with the prolonged interruption**	**SAIFI, pcs/year**	**The worst-case average number of interruptions**
PV PP e/s/w - passive	0h 25 min	node 3 for 1h 57 min	0,1	1,09
PV PP e/s/w - active	0h 21 min	node 3 for 1h 57 min	0	0
Passive network without PV PP	1h 28 min	node 3 for 5h 13 min	0,12	0,55

Active network without PV PP	1h 27 min	node 3 for 5h 13 min	0,08	0,56
Passive network with PV PP	1h 28 min	node 3 for 5h 13 min	0,12	0,55
Active network with PV PP	1h 27 min	node 3 for 5h 13 min	0,08	0,56

f. Indicators for continuity of power supply

From the research general conclusion can be done - to reduce SAIDI and SAIFI the greatest impact have PV PPs and in particular the approach for untraditional orientation of the modules - e/s/w.

IV. Conclusion

An analysis was made on double feed medium voltage network. Simulations have been done of the distribution network with and without management, with and without PV PPs. We proposed and have tested option for improving indicators for continuity of power supply SAIDI, SAIFI.

The simulations performed, results and conclusions are generally valid. They show that the most expensive option for the electricity distribution companies is to continue to build their networks in a traditional passive method without the possibility of active management and without penetration of PV PPs.

Since the main goal of any DSO is to improve the quality of the service, reducing interruptions will increase its competitiveness in a liberalized market. By assessing the loads DSO can lay the foundations of a model of network management. This model can be directly applied and subsequently be automated. Even at this first stage it will lead to better services from DSO. The proposed method of improving continuity is effective, but to be most effective it should be part of an overall strategy for comprehensive automation of distribution networks.

In summary, the examination of the tested options considered both active and passive distribution networks with and without PV PPs. They have helped to demonstrate the importance of the orientation of the PV PPs over the distribution network for the reduction of investment costs, increased level of connected photovoltaic power plants in the design of new or reconstruction of existing MV and LV networks. A key part of the research is the proposed option of combining differently oriented PV PPs to improve performance of the indicators for continuous power supply SAIDI, SAIFI. At the same time the large number of PV PPs will reduce energy dependence on fossil fuels, emissions under optimal investment costs and will accelerate the processes for the formation of a new strategy for development of the new smart energy system. It is clear that in the next years smart microgrids strategies will play a growing role in meeting local demand, enhancing reliability and ensuring local control of electricity.

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