SENS – TOOL FOR PLANNING AND OPERATION OF SMART DISTRIBUTION NETWORKS

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ABSTRACT

Continuous increase in the share of renewable energy sources and other low carbon units complicates the planning and operation of distribution networks. However, the newly created complexity also presents an opportunity for Distribution System Operators (DSOs) to start using the tools developed by the researchers and industry that will enable easier planning and operation of smart distribution networks. One such set of tools, named SENS (Smart Energy Network Systems), is presented in this paper. SENS enables four different applications in the planning (proposing an optimal topology of a distribution network) and operation (distribution network reconfiguration, calculation of flexibility provided by DSO's assets, and flexibility provided by a third party). We present a proof of concept in which four developed and implemented functionalities are verified and tested on different case studies defined in medium voltage distribution networks.

INTRODUCTION

Integration of distributed generators (DGs) and distributed energy resources (DERs) alter the paradigm of distribution networks planning and operation which were traditionally passive, with a unidirectional power flow. New technologies decrease greenhouse gas emissions and contribute to a financial benefit for end-users but they simultaneously aggravate a Distribution System Operators' (DSOs') job, who need to abandon previously used approaches and start relying on new tools and methods that are able to overcome the newly created challenges. New tools are in most cases fully automated and enable a wide range of power system simulations, including (optimal) power flow simulations [1,2], short-circuit calculations [3], harmonic power flow simulations [4], etc. By using these tools, DSOs are able to make analyses for different scenarios but they are more often used in detecting problems than in solving them.

To overcome the problem, there is a growing need for advanced tools that based on optimization, heuristics, and machine learning algorithms provide an optimal solution and directly help DSOs in making the decision relevant to the adequate planning and operation of distribution networks. One of the largest planning problems is determining the optimal topology of a distribution network due to stochasticity and variability of data, time-dependency of data, and the lack of data that is used in the process.

The authors in the paper [5] present a mixed integer linear programming (MILP) approach that proposes a joint optimal topology of two different networks considering their joint nodes, already existing cables, and traditional electrical constraints. A slight modification of the described approach is presented in [6], where the authors use joint cables instead of joint nodes and they base the determining of the optimal topology on the application of geographic information system (GIS). Optimization algorithms are often used together with genetic algorithms (GAs) and other similar algorithms based on heuristics in planning problems related to the optimal topology. MINLP problem of the optimal network expansion was solved using GA in [7], in which the authors propose the expanded topology, with new substations and cables which successfully mitigate identified obstacles.

Besides the planning problem, optimal topology can also be observed in operational time frame, where the network is reconfigured based on the events and the real-time state of the network. The difference is that the network reconfiguration operational problem relies on the existing elements of distribution networks and does not propose investment into new equipment. As mentioned before, integration of DERs causes different technical problems and increases the cost of distribution networks operation. Therefore, the authors in [8] propose an optimal stochastic reconfiguration methodology that leads to the cost minimization of smart grids with a high share of electric vehicles. Since distribution networks are radially operated in most cases it is important to add radiality constraints into network reconfiguration formulations. Therefore, a heuristic algorithm is used to check if a network has a radial topology and to minimize losses and improve voltage profiles [8]. Due to traditionally low observability, increased complexity of distribution networks and network reconfiguration itself, algorithms based on machine learning are used more often, as in [9], in which the authors use reinforcement learning where an algorithm learns the network reconfiguration control polity from a historical operational dataset.

Even though determining optimal topology and reconfiguring the network successfully solve some of the technical issues, detected problems can be more severe and their mitigation requires additional actions by a DSO. One of the methods for ensuring adequate network operation is the activation of flexibility services, either provided by DSOs assets other than switching devices or third parties. Integration and optimal operation of shunt capacitor banks showed applicability in decreasing power losses, total annual expenses, and voltage deviation but also in improving the voltage level, power factor, and voltage stability of the network [10]. Voltage magnitude in distribution nodes can be regulated by the joint operation of on-load tap changer (OLTC) transformers and converters through which DGs are connected to a network

[11]. In case of the additional need for flexibility, it is possible to activate third parties such as aggregated flexibility providers [12] or larger buildings that can contribute to the total demand change on their own [13].
As shown in the literature review, planning approaches that over-dimension distribution networks are being abandoned, and potential obstacles are solved by incorporating the optimal operation of smart distribution networks. There are multiple tools and approaches that enable analyses of smart distribution networks but also that directly propose a solution that helps DSOs in making the decisions that ensure adequate and safe network operation. However, the work in most papers is focused only on one potential method of solving technical issues, either through proposing a new algorithm or improving the existing ones and there is a lack of tools with multiple different functionalities that enable DSOs to test multiple approaches in securing adequate network operation. To overcome this issue, we present the application named SENS (Smart Energy Network Systems), an application that consists of the planning tool that proposes optimal topology of a medium voltage (MV) distribution network, both planning and operational tool that proposes a reconfiguration of an MV network in order to obtain optimal solution and two operational tools that calculate the flexibility needs potentially provided by DSOs assets or a third-party.

METHODOLOGY

SENS application is developed on open source technologies allowing further upgrades and the addition of new functionalities or improvement of the existing ones. It consists of four different tools that can be applied to different aspects of the planning and operation of smart distribution networks:

1) Distribution network's optimal topology
2) Distribution network's reconfiguration
3) Flexibility provided by DSO's assets
4) Flexibility provided by a third party

Distribution network's optimal topology

The first potential application of the SENS tool is its use in the planning of MV distribution networks by proposing an optimal topology based on a GA and data stored in the GIS-based tool, as described in [14]. The tool presented in this paper is a significant upgrade of the work [14], where the functionalities remain the same as before but the significant improvement is achieved in the visualization and the presentation of the results. The input in the tool is a set of files containing information about existing substations in a network, the cost of connecting them, and technical characteristics of lines used for connecting the substations – material and section of a line and a line's length-to-section ratio. Besides the set of files, a user must define energy, cost, and genetic algorithm parameters that will help in obtaining the optimal solution to the defined problem. Application of the tool is not constrained by the network's initial configuration, i.e., it can be used in cases of both meshed and linked (radial) distribution networks. Additionally, the tool uses data related to the existing network and elements but also in cases where it is needed it proposes the optimal placement of new cables or building of new substations if some of the network's technical constraints are violated. The goal of the tool is to propose a new network topology or a reconfiguration of the existing one, with the objective of minimizing the costs of the network's elements connection and minimizing the network losses without the violation of defined constraints.

Distribution network reconfiguration

Unlike the first SENS tool that provides an optimal distribution network topology only in the planning aspect, a tool used in a network reconfiguration can be used in the operation aspect as well. The input in the tool is a file containing relevant information about the network's elements, e.g., technical characteristics of MV lines and cables and a file with values of demand of all MV consumers or MV/LV substations and production of distributed generators connected to the observed network. The used mathematical model is based on the exact, nonconvex optimal power flow (OPF) formulation, defined with equations (1)-(3), where x_{switch} is a binary variable that defines if the line ij is switched on or off. Equation (4) defines that the number of lines is by one smaller than the number of nodes in a network, which is a common constraint for ensuring the radiality of distribution networks.

$$P_{ij,t} = P_{j,t}^{load} - P_{j,t}^{DG} + v_{i,t} g_{sh,t} + x_{switch,ij,t}\left(i_{ij,t} r_{ij} + \sum P_{jk,t} - \sum P_{ij,t}\right) \quad (1)$$

$$Q_{ij,t} = Q_{j,t}^{load} - Q_{j,t}^{DG} - v_{i,t} b_{sh,t} + x_{switch,ij,t}\left(i_{ij,t} x_{ij} + \sum Q_{jk,t} - \sum Q_{ij,t}\right) \quad (2)$$

$$v_{i,t} - v_{j,t} = 2\left(r_{ij} P_{ij,t} + x_{ij+} Q_{ij,t}\right) - \left(r_{ij}^2 + x_{ij}^2\right) i_{ij,t} \quad (3)$$

$$\sum x_{switch,ij,t} = N - 1 \quad (4)$$

The objective function of the network reconfiguration problem is not unambiguous and it depends on the preferences of a DSO or other user of the tool. Some of the potential objective functions are the minimization of losses or maximization of the CAIDI or other indicators of the security of supply. The objective function of this tool is the minimization of losses which is additionally constrained in a way that allows the change of network topology only once per day. This constraint restricts often changes in the topology and the too large number of switching of devices used in the reconfiguration of the network.

Flexibility provided by DSO's assets

Most DSOs own assets that are already installed in a distribution network and whose rescheduling their operation can lead to the improvement of technical conditions in a network.. Such assets are OLTC transformers, shunt capacitors, inverters, voltage-dependent loads, etc. As a part of the SENS application, the mathematical model presented in [15] has been implemented to calculate the potential flexibility that

DSO's assets can provide. The tool is also based on the OPF formulation, with the slight extension of equations (1) and (2) and the addition of several other constraints related to the operation of observed devices. The presentation of the full, detailed model is outside the scope of this paper. Same as in the previous two tools, a set of input files is needed in order for the tool to be able to calculate the optimal solution of the given problem. Together with the common information about the network's topology and technical characteristic of network's elements, additional files containing information about the flexibility providers are needed. These files define the location of the assets, e.g., nodes to which inverters are connected and the information relevant for determining the assets' operation change, e.g., minimum and maximum power output of DGs, number of taps and the step of change of OLTC transformers.

Flexibility provided by a third party

Besides using their own assets, DSOs often rely on a third party that can provide the required flexibility service. Third parties include large buildings and industrial plants connected to an MV network but also aggregated LV end-users connected to the same or multiple MV/LV substations. Based on the input which consists of network topology and technical characteristics data, demand and generation curves, and information relevant to the flexibility calculation, e.g., nodes to which flexibility providers are connected and the upward and downward flexibility bounds, an OPF algorithm suggests which flexibility providers should be activated and calculates the value of demand that should be decreased or increased in order to mitigate issues in the network. The described functionality of the tool is just a basic approach to the calculation of the needed flexibility. Since the SENS application and all tools that are integrated into it are based on open source programming languages, it is possible to extend the approach with the inclusion of market and price signals, observing the reservation of flexibility and its activation closer to real-time, etc.

VERIFICATION AND CASE STUDIES

Case study 1

The tool is used in the real-world Croatian case study to find an optimal topology of the network in defined period. Since the basis of the tool has been used by the national DSO in numerous technical studies for the planning of MV distribution networks there is no need for its verification prior to the application in the network's planning.

The tool is tested on an existing urban 10 kV distribution network with 23 substations, from which 22 of them are 10/0.4 kV substations used for supplying LV end-users and the remaining 110/10 kV substation is a connection to a transmission network. Before running the algorithm, it is necessary to define energy parameters, e.g., permitted voltage drop, maximum number of substations per mesh, cost parameters, e.g., energy loss costs, and genetic algorithm parameters, e.g., number of generations, population size. Two different sets of parameters are designed in case studies 1a) and 1b) where the same input data was used in the defined planning problem. The definition of these parameters affects the optimal solution proposed by the tool, which is shown in Figure 1 and Figure 2, with a clear difference in the proposed topology. Full lines represent the cables that already exist, need to be placed in existing corridors, or need to be placed in corridors and routes that need to be built. The dashed line represents the optimal separation point in the grid since despite the meshed network in the planning process, it is operated as a radial, and therefore, it is necessary to propose a place of separation of mesh into radials.

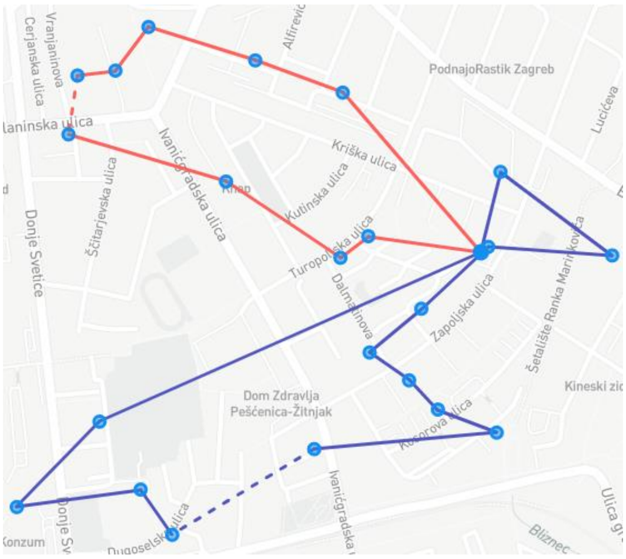

Figure 1 Proposed optimal topology - case study 1a)

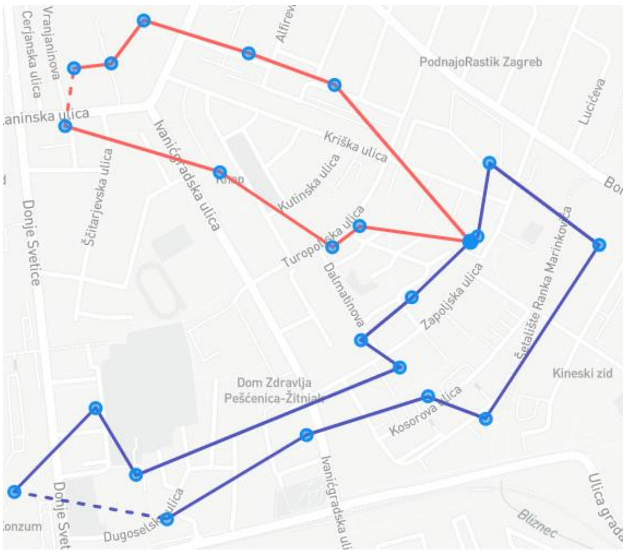

Figure 2 Proposed optimal topology - case study 1b)

Case study 2

Unlike the tool presented in Case Study 1, the network reconfiguration tool has not yet been used so it needs to be verified before further use. The accuracy of the solution obtained by the model integrated into SENS is verified by running simulations on the IEEE-33 node distribution system, a common distribution network used in solving network reconfiguration [16]. In the first step of verification, we check if the developed tool proposed the same topology as the one in [16]. Figure 3 IEEE-33 node networkFigure 3 shows the topology proposed by our tool, which is the same as the example in the literature, which verifies the first step.

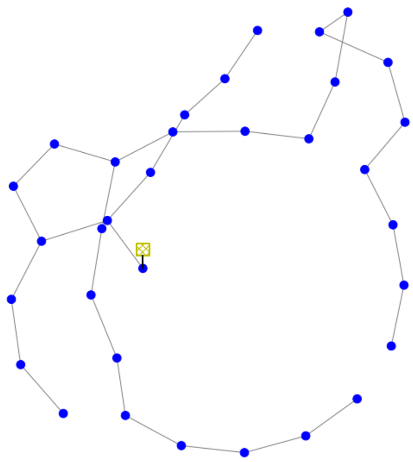

Figure 3 IEEE-33 node network

In the second step, we compare nodal voltages obtained by the developed tool to those obtained by the pandapower tool. As can be seen in Table 1, there are no significant deviations in results obtained by two different tools, making the second step of verification complete.

Table 1 Voltage magnitude comparison

Voltage deviation (%)			
Minimum	Maximum	Average	Median
0.00	0.03	0.01	0.00

Based on the verification results, the developed tool gives accurate solutions, which makes it suitable for full integration into the SENS application and further use in solving the reconfiguration problem.

Case study 3

As mentioned before, different devices that are already installed in distribution networks can contribute to the improvement of technical conditions just by rescheduling their operation. One of the potential applications of such an approach is the provision of flexibility service at the TSO/DSO interface. There are cases when more than one solution is feasible, which leads to the creation of a region instead of only one feasible point. One such region calculated with the tool that is integrated into SENS is shown in Figure 4. Rescheduling the operation of assets in a way that will ensure the reaching of any point within the calculated PQ region ensures resolving overvoltage, undervoltage, congestion, or other similar technical problems in a distribution network.

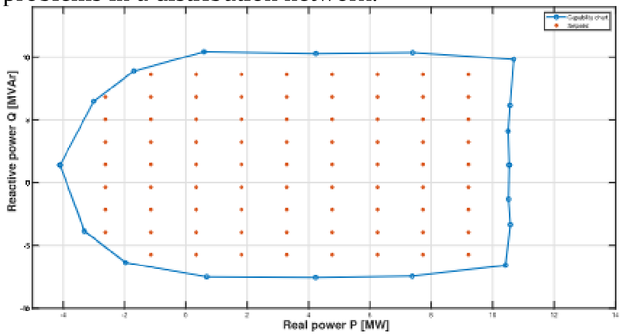

Figure 4 PQ region at the TSO/DSO interface

Case study 4

The final case study was designed to test the functionality of the developed tool that calculates the value of the flexibility that can be provided by a third party. In Case study 4, we modeled a real-world Croatian MV distribution network. Each MV/LV substation is modeled as a PQ node, with values of active and reactive power defined from the measurements collected at substations. End-users connected to one substation are assumed to be aggregated and can change their consumption in cases when technical conditions in a network need to be improved. Figure 5 shows the value of flexibility that needs to be activated in order to bring values of network currents and voltages within allowed boundaries.

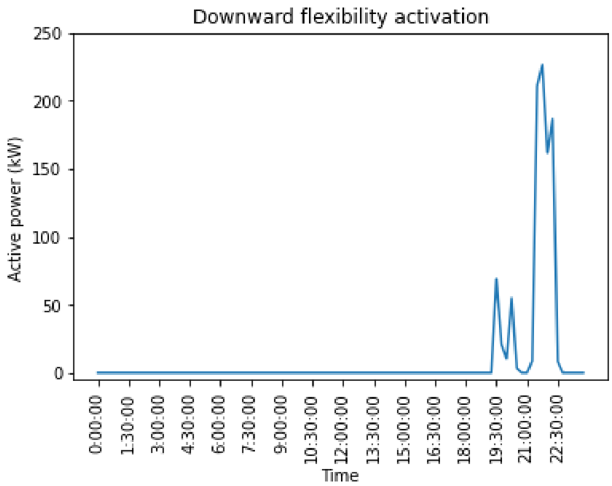

Figure 5 Calculated downward flexibility

CONCLUSION

Integration of new technologies and changes in the traditional behavior of end-users in distribution networks creates numerous challenges in planning and operational aspects for DSOs. To make the planning easier and to ensure adequate and safe operation with continuous integration of new technologies, DSOs need to rely on a set of new tools to enable different network analyses and help in making decisions. SENS, one such tool is presented in this paper. SENS consists of four tools that can be used in the planning and operation of smart distribution networks. Tools propose optimal topology of a network based on the existing and potential newly installed elements, network reconfiguration by optimal operation of switching devices and it calculates the needed flexibility that can be provided either by rescheduling the operation of DSOs' assets or engaging a third party. Each of the four tools is tested on a specific case study, with the results proving the presented concept. The largest benefit of SENS is its open source implementation which allows the upgrade of existing functionalities but also the addition of new ones.

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