ACTIVE DISTRIBUTION NETWORK PLANNING BASED ON A HYBRID GENETIC ALGORITHM-NONLINEAR PROGRAMMING METHOD

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ABSTRACT

This paper proposes a planning method for active distribution networks that determines the optimal network reinforcement and expansion plan considering ancillary services provided by distributed generation (DG) units. The proposed method calculates the network's investment and operational costs in order to meet the future load demand as well as the connection of new loads and new DG units. Results on a 21-bus distribution system validate the method's performance.

INTRODUCTION

Distribution network planning (DNP) determines the optimal location and capacity of new network components, such as new distribution lines, transformers and capacitors, in order to cope with the future load demand and guarantee the safe operation of the system. The main objectives of the DNP problem is to minimize the investment cost of new network components and the operational cost, such as power losses and maintenance costs. The traditional DNP problem is solved considering a given load forecast along a planning horizon.

Nowadays, power distribution networks are facing the challenge to accommodate an increasing amount of distributed generation (DG), mostly based on renewable energy sources (RES). Traditional DNP approaches simply consider DG units as negative loads. However, national policies and advanced information and communication (ICT) technologies facilitate the integration of energy storage systems, the control of DG units, the coordinated control of all network components and the implementation of load response schemes [1]. Thus, the distribution networks are evolving from passive to active distribution networks (ADNs). Therefore, new DNP tools need to be developed in order to exploit the capacity and control capabilities of the DG units.

DNP is a complex mixed integer non linear programming (MINLP) problem due to the nonlinearity of the power flow equations and the integer decision variables. A review of DNP models and methods can be found in [2]. In [3], the impact of dispatchable DG on the DNP is examined. The control capabilities of the distributed energy recourses (DER) are effectively incorporated into the planning process deferring network reinforcements while decreasing the network's operational costs [4]–[6]. In [7], the financial and environmental benefits of integrating demand response (DR) schemes and DER allocation into the planning framework are examined. The DNP method presented in [8] incorporates DER control, DR and online reconfiguration considering a simplified mixed integer linear programming (MILP) model.

High DG penetration may cause several operational issues in the distribution networks such as voltage rise and/or line congestion. To deal with these issues additional network reinforcement should be performed, which leads to additional investment costs. Installing energy storage systems (ESSs) to the network could mitigate voltage rise and alleviate line congestion. However, the investment and maintenance cost for installing ESSs is considerably high. Control of the active and reactive power of the DG units could deal with these issues and defer potential investment costs on network reinforcement.

This paper proposes a hybrid genetic algorithm (GA) - non linear programming (NLP) approach for the planning of ADNs. More specifically, the proposed method minimizes the network investment and operational costs. The network investment costs include the expenditures for the network reinforcement and expansion in order to meet the future load demand as well as the connection of new loads and new DG units. The operational costs include the energy losses during the planning period. Furthermore, the effects of the control of DG active/reactive power in the solution of DNP problem are examined and the cost of the ancillary services provided by the DG units is included in the DNP solution. Based on historical and forecasted data, multiple load/generation scenarios are considered in order to efficiently capture the stochasticity of load demand and renewable generation. The proposed method is tested in a 21-bus distribution test system and the results present the trade-offs of integrating the active network management into the planning process.

PROBLEM FORMULATION

DNP is mainly a demand-led process and it is mainly solved considering a given load growth forecast along a planning horizon. The load growth of an area served by the Distribution System Operator (DSO) is the most important factor influencing the reinforcement and expansion plan of the distribution network. The most common time scales of load forecasting are: i) long-term, with a time horizon of 15–20 years and ii) short-term, with a time horizon of up to 5 years [9]. Detailed and accurate load forecasting is a difficult process since it depends on various and sometimes unrelated factors. Thus, statistical data are used to enhance load forecasting and multiple scenarios of load growth are examined by the utilities.

Most utilities perform their network planning analysis based on load demand forecasting and they often ignore the integration of renewable DG. DG units are currently connected to the network considering passive operation, the so called "fit and forget" approach. In this approach, power flow analysis is performed to examine the feasibility of the network connection considering that DG units operate under constant power factor. Neglecting DG leads to inefficient planning and future operation of the distribution network.

In this paper, the analysis of the DNP problem is made under the following assumptions:

- The load is represented as constant real and reactive power.
- The shunt capacitance of the distribution lines is omitted.
- Smart metering is fully deployed throughout the network.
- The DG units are assumed to be private investments and their type, site, size and installation time period are considered pre-determined.

The DNP problem is modelled as a (MINLP) problem with the following objective function:

$$TC = \sum_{t \in T} \frac{1}{(1+r)^t} \left(INC + OPC + ANC \right) \quad (1)$$

The objective function (1) of the DNP problem is the net present value of the total investment, operational and active network management cost during the planning period T with an interest rate r. More specifically:

- *INC* represents the total investment costs for the reinforcement of the existing distribution lines and the addition of new ones.
- *OPC* refers to the operational costs that include the total cost of energy losses during the planning period.
- *ANC* represents the cost of enabling the active management of the distribution network. It is the cost that is paid to the DG owners that provide ancillary services to the network.

The constraints of the DNP model are the active and reactive power flow balance in every bus of the network; the capacity limits of each existing and added distribution line; the bus voltage limits; the radial operation of the network.

Active Network Management

By incorporating active network management (ANM), renewable generation can be controlled by managing the active and reactive power of the DG units [10], [11]. It is assumed that an aggregator operates the renewable generation in its served distribution system [12]. The aggregator a) receives real-time measurements from smart meters, b) determines the appropriate set-points of the DG units, and c) sends these set-points to the DG units. The adoption of ANM can defer the investments on new network components, and can also decrease the network's power losses. Therefore, it is crucial that modern planning tools integrate ANM schemes to identify alternative cost-effective planning solutions with better technical and economic balance.

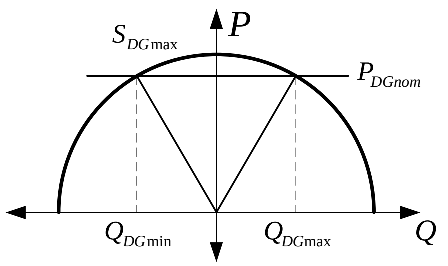


Figure 1–Inverter reactive power capability curve.

Depending on the technology utilized by the DG units, their operation at leading, lagging or unity power factor is possible. Therefore, it is considered that DG units are able to supply or absorb reactive power via their inverter interface, as shown in Figure 1, within some limits in order to secure the safe operation of the distribution network. To operate the DG units under adaptive power factor (APF), the installation of oversized inverters may be required.

Furthermore, periods with strong generation may lead to the violation of the thermal and voltage constraints of the distribution network. In order to confront these occasions, the control of the reactive power of the DG unit may not be sufficient. In these cases the curtailment of the active output power of the DG unit is needed. However, in contrary to the reactive control of the DG unit, active power curtailment should be partially or totally refunded to the DG owner depending on the regulatory framework. It is assumed that the total curtailed active power from each DG unit should be less than a percentage of the potential output power that would have been produced.

The variables associated with the ANM implementation, e.g., power angle of the DG unit and active power curtailment, are discrete variables. For the sake of simplicity and in order to reduce the complexity of the DNP problem, the aforementioned variables are taken as continuous variables. This assumption is acceptable, since the developed DNP model addresses planning issues and not operational ones.

SOLUTION METHODOLOGY

In the DNP methods where no renewable DG is considered, the optimal planning solution was calculated based on the maximum load conditions and the mean load for the calculation of energy losses. In the planning of ADNs, the stochastic behaviour of DG and load demand over a time span, e.g., yearly, should be taken into account. The consideration of all possible values of load and generation over the planning period results in a large-scale computational simulation making the planning process practically infeasible.

Probabilistic models can be used to address the uncertainties of the planning data. Suitable probability density functions, e.g., Weibull, Gaussian, Beta, etc., can model the stochastic behaviour of the input data and probabilistic power flow calculations can be used for the solution of the DNP problem. However, probabilistic calculations of the nonlinear power flow equations may lead to impractical computation times.

Thus, this paper considers a reasonable number of load and generation scenarios based on historical data. More specifically, the *k*-means clustering method groups the available load and generation scenarios (e.g., the complete yearly load and generation profiles with a resolution of one hour, i.e., 8760 values per curve) into *k* clusters, which have similar stochastic behaviour as the complete list of scenarios.

A hybrid GA–NLP methodology is employed for the planning of ADNs. The methodology involves the following steps: i) chromosome coding, ii) creation of initial population, iii) chromosome evaluation, and iv) crossover, mutation and next generations. Each chromosome depicts the investment variables for the addition and reinforcement of distribution lines and they are coded as integer variables. To create radial networks as initial population, for a new load bus connection, first an available route is randomly selected and then its conductor type is randomly chosen. For the candidate lines for reinforcement, a conductor type with equal or higher ampacity is randomly chosen. Each candidate solution contains the integer variables with the network investment variables, so the network topology is provided. Afterwards, the feasibility of the candidate planning solution is analyzed using a commercial NLP solver. A penalty cost is assigned to the infeasible solutions, instead of simply rejecting the solution. A two-point crossover operator is applied to the population of the mating pool to create an offspring population for the next generations. The mutation operator will be used in a percentage of the mating pool population. The optimization procedure terminates when a maximum number of generations is reached or the solution is not improved after a certain number of generations.

RESULTS

The proposed DNP method is applied to the modified 21-bus distribution network [13] shown in Figure 2. The 21-bus distribution network is a 13.8 kV network with one substation, 4 existing load buses and 16 future load connections. The dashed lines in Figure 2 depict the possible connections of the future loads. The conductor type of the existing lines is given by the number next to them in Figure 2. The technical and economical characteristics of the available conductors are presented in Table 1. Three wind farms of 3 MW each are planned to be connected at buses 6, 10 and 19. The hourly load and wind generation profile per year are acquired from the case study of [14]. The data are grouped into 20 clusters using *k*-means method resulting in 20 load/generation scenarios per year. The duration of the planning period is equal to 10 years with 2% annual load growth rate. The energy loss cost is equal to 0.40 $/kWh. The cost of enabling ANM is equal to 0.02 $/kWh. The interest rate is equal to 7%.

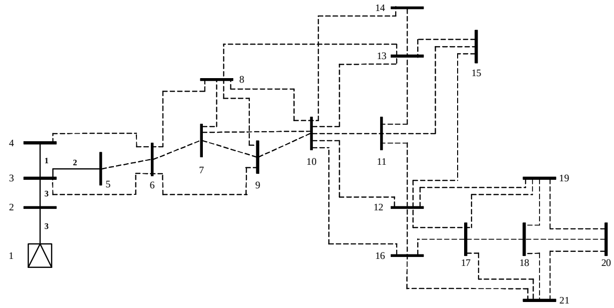


Figure 2–The 21-bus distribution network.

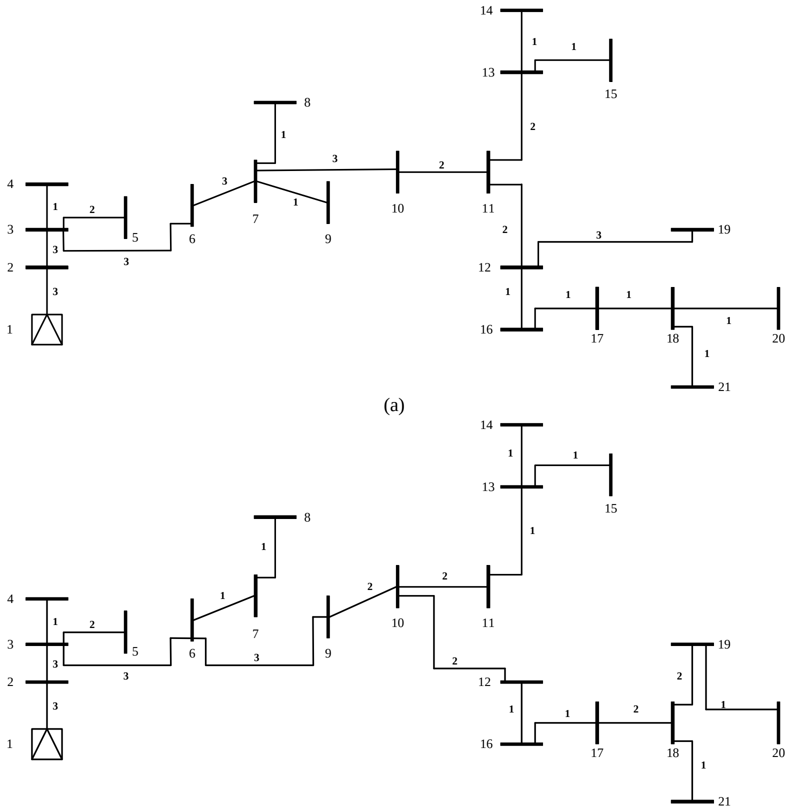
Table 1 Technical and economical characteristics of the available conductors

Type	R (Ω/km)	X (Ω/km)	Ampacity (A)	Cost ($/km)
1	1.0145	0.4679	158	10 000
2	0.5205	0.4428	250	40 000
3	0.2006	0.4026	453	90 000

Three different cases were examined:

- Case 1: The DNP problem is solved without considering any control of the DG units. In this case the cost of the ANM is equal to zero.
- Case 2: The DNP problem is solved considering the active and reactive power of all available DG.
- Case 3: The DNP problem is solved considering the active and reactive power of the wind DG unit placed at bus 10.

Figure 3 illustrates the optimal planning solutions in Cases 1–3. In Figure 3, the number next to the distribution lines represents their conductor type. The planning solution in Case 1 is illustrated in Figure 3(a) and its total cost is 1191 k$. In Case 1, the total network investment cost is equal to 957 k$ and the total energy loss cost is equal to 234 k$. The planning solution in Case 2 is illustrated in Figure 3(b) and its total cost is 1169 k$. The network investment cost in Case 2 is equal to 725 k$, which is 24.2% lower than the network investment cost in Case 1, and the energy loss cost is 165 k$, which is 29.2% lower than in Case 1. However, the expenditures for the ANM implementation in Case 2 are equal to 279 k$. It should be noted however that ANM might be in place as part of energy policies to facilitate customer awareness and participation, in which case these expenditures should not be considered. The planning solution in Case 3 has the same network topology as in Case 2 and it has the lowest total cost,



(a)

(b)

Figure 3–The 21-bus distribution network: (a) Optimal planning solution in Case 1, (b) Optimal planning solution in Cases 2 and 3

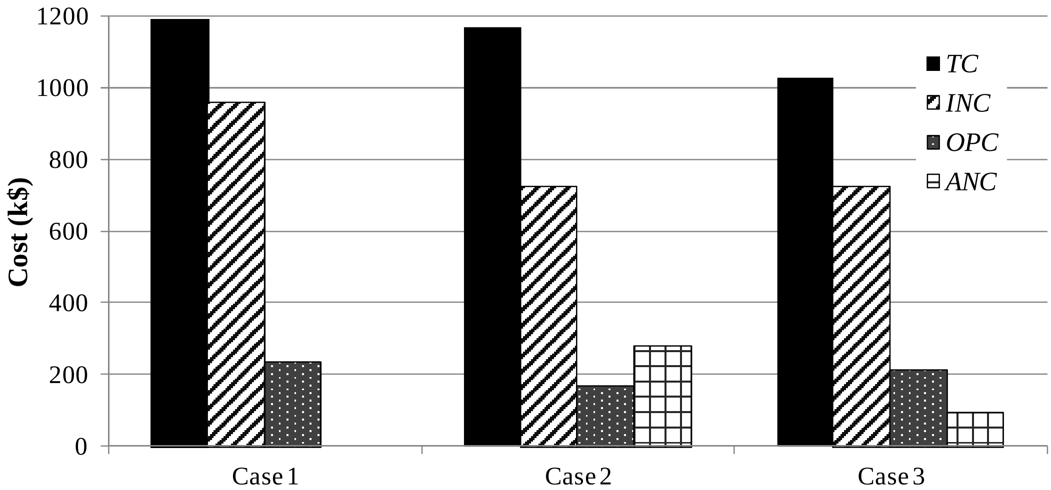


Figure 4–Cost analysis of Cases 1–3

which is equal to 1028 k$. In Case 3, only the active/reactive control of the wind farm in bus 10 was allowed drastically decreasing the ANM costs. This limitation had effect only on the operational costs of the network, while the investment costs remained the same as in Case 2. The detailed cost analysis of the Cases 1–3 is illustrated in Figure 4. It must be noted that in Case 3 the active power curtailment was enabled only in the load/generation scenarios that the actual DG power was greater than 90% of the nominal DG active power.

CONCLUSION

The proposed method provides the optimal planning solution of ADNs. The planning framework is based on hybrid GA-NLP optimization procedure that considers multiple load/generation scenarios and the integration of different ANM schemes into the planning process providing new dimensions to the DNP problem. In fact, results show that a considerable decrease of costs can be achieved when the control of DG units' active and reactive output power is considered, highlighting the importance of ADNs. The proper tuning of the GA parameters, the chromosome integer encoding, the efficient implementation of the crossover and mutation operators along with the creation of the initial population are the key features for the effective application of the GA in the planning of ADNs.

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