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DECISION SUPPORT TOOL FOR THE DEVELOPMENT OF POWER DISTRIBUTION NETWORKS BASED ON AI PLANNING

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ABSTRACT

Long-term planning of interconnected electrical distribution networks consists in imagining the evolution of the existing network towards a target network, respecting the objectives and constraints set by the DSO, according to national and local energy evolution scenarios and with a time horizon of several decades. At present, there is no tool that can automatically and optimally propose target networks, as well as the annual intermediate networks that would allow reaching them. Automated planning (AI planning), a sub-field of Artificial Intelligence, is a model-based approach to action selection. The objective of this paper is a first attempt of a decision support tool for DSOs, based on AI planning and electrical computations, to help them finding the aforementioned intermediate networks.

INTRODUCTION

Long-term planning of distribution systems involves the development of master plans that provide direction for system development. The ideal network may be far from the initial network, and the set of basic changes from the initial network to the final network can be complex, especially if the network is large. The mission of the distribution system operators (DSOs) is to establish these master plans and plan the work in the short term based on technical and economic calculations. If the previous calculations are done with the help of software, the planning work itself, i.e. imagining the network topology and the evolution strategies, is done by hand thanks to the know-how of the DSOs. Given the growth of renewable energies connected to the distribution network and the increase in electric vehicles, the distribution network will undergo significant changes in the future. Thus, there is a growing interest in developing decision support tools for the planning of electrical distribution networks.

In the literature, many articles propose planning algorithms with different objective functions (cost, reliability for example) and constraints. They can be classified into three categories: expansion-planning, growth of an existing system and operational planning. Faced with the complexity of the optimization problem, most of the proposed algorithms either requires linearization steps or are based on heuristics/metaheuristics that require a prior tuning of the various parameters and are therefore difficult to implement and use [1]. To face this strong usability constraint, Artificial Intelligence (AI) planning is of great interest. Indeed, after having modeled the problem, the domain and the set of rules, AI planning systems generate plans (as an

answer to the specified input problem) [2] which can then be studied in post-processing by the DSOs either manually or automatically. This field of artificial intelligence has been little applied in the field of power systems. In one example in [3], AI planning is used to find the optimal settings of an on-load tap-changer and a mechanically-switched capacitor to regulate the voltage of a transmission substation for each hour of the day.

The objective of this paper is a first attempt of a decision support tool for DSOs, based on AI planning and electrical computations, to help them finding intermediate networks to reach the target network.

BACKGROUND AND HYPOTHESIS

Power systems planning

The most common urban architecture is the “secured feeder” shown in Figure 1.

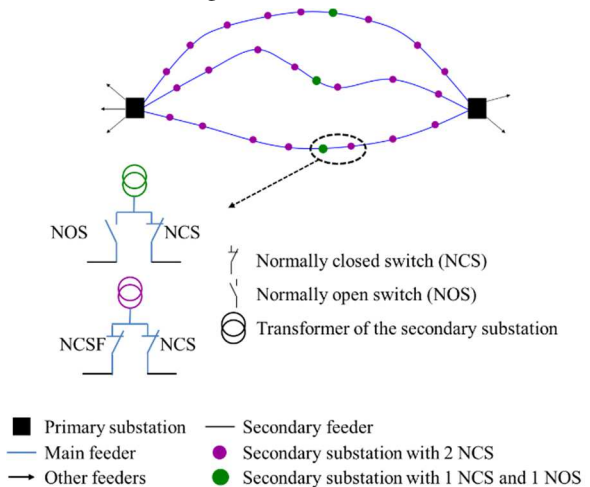


Fig.1 Urban secured feeder architecture, NCS refers to normally closed switch and NOS refers to normally open switch.

Each primary substation (black square) is connected to another primary substation via a set of electric lines, called main feeders (blue lines), supplying secondary substations (circles). Each secondary substation is connected to a main feeder via two remote-controlled or manual switches. All of these switches are normally closed (small circle) except one (in the big circle) to ensure the radially of the architecture i.e., each load is supplied by only one primary substation in normal operation. In case of fault, DSOs can reconfigure the grid: secondary substations are supplied by another primary substation waiting for the field crew to carry out repairs. All the normally open switches are

always remotely controlled. A technical and economic analysis determines the share of normally closed switches remotely controlled. In practice, distribution networks have been developed gradually and some urban networks are not exactly a “secured feeder”. For example, they can have secondary feeders (called antenna in the case of rural or peri-urban areas) or are looped on the same primary substation. In the latter case, if an outage occurs on this primary substation, secondary substations cannot be reenergized. We assume that the target grid is an ideal secured feeder which respects the DSOs’ objectives and constraints we will describe in the next section. Consequently, both the initial and target grids have the same primary and secondary substations and differ only by their connections and their normally open switches. In this paper, we are focused on the transition from the initial grid to the target grid, i.e. the intermediate grids.

Automated planning

AI planning, a sub-field of Artificial Intelligence, is a model-based approach to action selection [4]. It aims to study and design, domain independent general approaches to the problem of finding a sequence of actions to achieve a goal. In AI planning, the dynamics of the domain of interest are expressed on a high-level representation language. Thus, it represents a cost-effective method for quickly setting up a solver since representations can be more human readable and easier to modify.

The AI Planning representation language used in this work is the Planning Domain Definition Language (PDDL) [5]. The planning model, i.e. the dynamics of the domain of interest, their possible actions and the conditions to attain some goal, is written as a compact representation of an AI planning task in PDDL-Code. The domain is composed of predicates which characterise the properties of the objects and a set of non-instantiated actions which establish the ways to move from one state to another. The problem is composed of:

- objects which define the task relevant things in the world;
- an initial state s_0 which represents the starting configuration of the world;
- a goal state s_g which describes the desired predicates that we want to be true.

The domain definition is a general model while the problem definition is a specific problem instance.

The main purpose of modelling the distribution network as a planning model in PDDL is to use AI planning systems. In the last 20 years, the automated planning community has developed a variety of state-of-the-art planners able to scale up to large problems thanks to the use of effective domain-independent heuristics which allow to guide the search. The algorithms embedded in planning systems search for paths in the search space through different search strategies [6].

DECISION SUPPORT TOOL

Figure 2 presents the different steps of the planning decision support algorithm. It takes as input the initial and the target network set by the DSO. The AI planning

module generates a list of actions that, when applied to the topology of the initial network, transform it into the desired topology of the target network. To do so, the dynamics of the domain, all possible actions and the conditions allowed by the DSO were defined in an AI planning model after several interviews with DSOs. Then, in the post-processing module, actions from the generated list are clustered so that the intermediate networks respect DSO’s technical, topology and economic constraints.

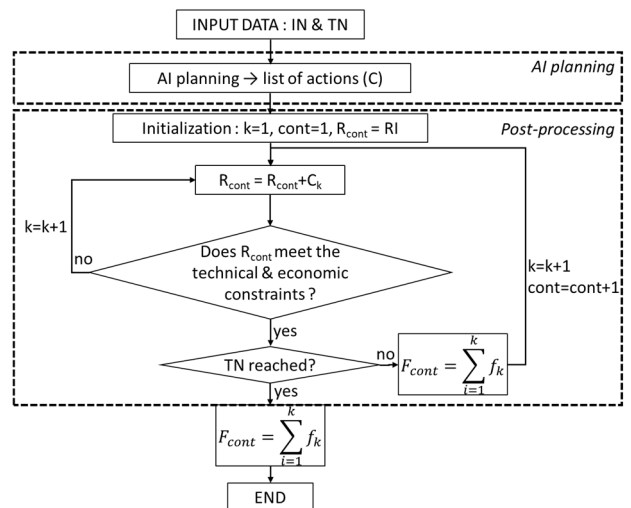


Fig. 2 Planning decision support algorithm

Variables used in Figure 2: IN (Initial network), TN (Target network), C (list of actions found), k (index of actions), cont (index of intermediate networks), R_{cont} (Intermediate network n°cont), f_{cont} (total cost of the intermediate network n°cont) and f_k (total cost of action n°k).

Definition of DSO’s rules

DOS’s interviews enable to set six rules for the AI planning block.

- Rule 1: Lines cannot be created if they do not belong to the final network.
- Rule 2: There is no closed loop between two primary substations i.e., a normally open switch is required to ensure a radial operation.
- Rule 3: There is only one connection between two nodes (distribution/source) i.e., parallel lines are modelled as an equivalent reinforcement (line with a higher section).
- Rule 4: Lines which have to be replaced (either a reinforcement or change of technology in case of a high rate of failure) are treated in the post-processing phase.
- Rule 5: For urban areas, the number of connections of secondary substations are between 2 and 3.
- Rule 6: Lines are tagged as mutable or not mutable. For example, non-mutable lines can

refer to recent lines (lower than 40 years since the cable technology is synthetic).

AI planning module

We decided to model the distribution network domain as a four-action PDDL domain. The conjunction of the defined actions and predicates guarantees that all DSO rules are satisfied (as long as the initial and target networks satisfy those rules). As an example, in Code 1, we present our solution for the PDDL representation of the removal of an open line between two substations. This action takes as parameters two substations s_1 and s_2 (each substation can be primary or secondary). For this action to be applicable, the current network state (i.e. the current state of the world) must satisfy the following conditions:

- There exists an open line between s_1 and s_2 .
- Connections going in or out of s_1 and s_2 are allowed to change (i.e. they are mutable).
- For s_1 and s_2 : either it has three connections, or it is a primary substation. Notice that the modelled domain does not allow an open line between two primary substations.

This action will change the current network state in the following way:

- The open line between s_1 and s_2 will no longer exist.
- New lines can be connected to and from s_1 and s_2 .

```
(:action remove_openLine
:parameters (?s1 - substation ?s2 - substation)
:precondition (and
  (open_line ?s1 ?s2)
  (or (full ?s1)
      (is-primary ?s1))
  (or (full ?s2)
      (is-primary ?s2))
  (mutable ?s1)
  (mutable ?s2)
)
:effect (and (not(open_line ?s1 ?s2))
  (not(open_line ?s2 ?s1))
  (not(connected ?s1 ?s2))
  (not(connected ?s2 ?s1))
  (not(full ?s1))
  (not(full ?s2))
  (available ?s1)
  (available ?s2)
  (removed ?s1 ?s2)
  (removed ?s2 ?s1)
))
```

Code 1: PDDL action of the distribution network domain representing the removal of an open line between two substations.

The AI planner takes as input the aforementioned PDDL domain and a problem instance. As a result, it generates a plan as an answer to the specified input problem. The modelled domain and the problem instance were fed to a planner that attempts first to solve the problem using SIW+ [7], and if that fails then BFS(f) [8] is invoked. This configuration allows to find a solution as fast as possible,

while retaining completeness. The AI planner was run with a timeout of 10 seconds and 2GB of RAM.

Post-processing module

The post-processing allows in a second time to group the actions obtained by the planner in order to respect technical, topological and economic constraints. The technical constraints are the following:

- The voltage at each node of the network must be within +/- 5% of the nominal voltage;
- The current in each conductor must be lower than the maximum admissible current.

A classical load flow calculation is used to verify the above constraints.

The topological constraints are related to the need to be able to reconfigure the network after a fault. Thus, each secondary substation must be connected to two primary substations. Normally open switching devices allow for radial operation of the network. The algorithm to verify this constraint is based on a graph search.

The economic constraint incorporates the fact that the DSO can allocate an annual work budget that allows several actions to be grouped. It is assumed here that the average total construction cost of a line is 500 k€ and that of a normally open line is 12 k€. Removing a line and relocating a normally open switching device have a negligible cost. At each action applied to the network, if the constraints are respected then this action creates a new intermediate network. If not, the next action is applied and so on until a network respecting the constraints is obtained.

APPLICATION ON A REAL TEST CASE

Test case description

The developed algorithm is tested on a part of a real French network represented on Figure 3 and comprising 18 nodes.

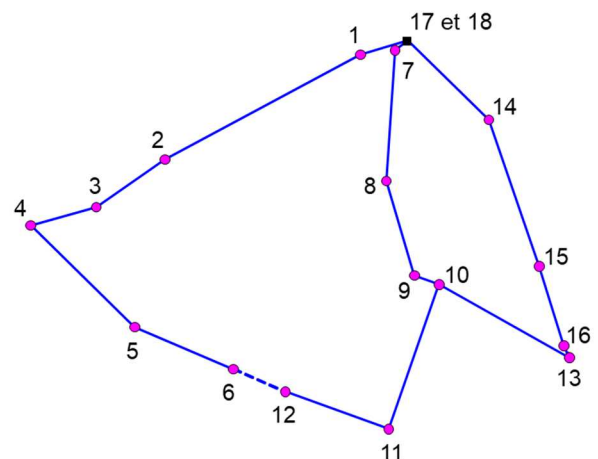


Fig. 3 : Initial network (open line : 6-12 and 13-16)

The 16 circles represent an aggregation of secondary substations and the two squares (which are merged on the figure because they are close) represent two primary substations. The lines with normally open switches are

shown in dotted line. The structure of the primary substations is given in Figure 4. The total power consumed is 19.7 MW (including Joule losses).

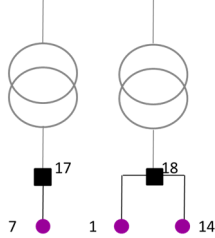


Fig.4: Initial connection of the two primary substations.

In order to propose a target network, the algorithm implemented in [9] allows to optimize the network according to a criterion of consumer equality. Each feeder (from one primary substation to another) must have the same PL product, i.e. the total power of the main feeder multiplied by its total length is constant whatever the feeders. Also, the normally open switches are placed so that the main feeder is split into two equivalent PL product areas. Thus, a long feeder will be lightly loaded and a short feeder will be heavily loaded so that the probability of power cut is identical.

To reach the target network obtained and depicted in Figure 5, five lines must be removed from the initial network, five new lines must be built and two existing lines (6-12 and 17-7) must be reinforced. Since the reinforcement decision is based on a technical criterion, it is not taken into account in the AI planning module but in the post-processing. Thus, as the DSO has an interest in deferring its investments as much as possible, a reinforcement decision will only be activated in case of constraints detected on an intermediate network if it has a positive impact on the network.

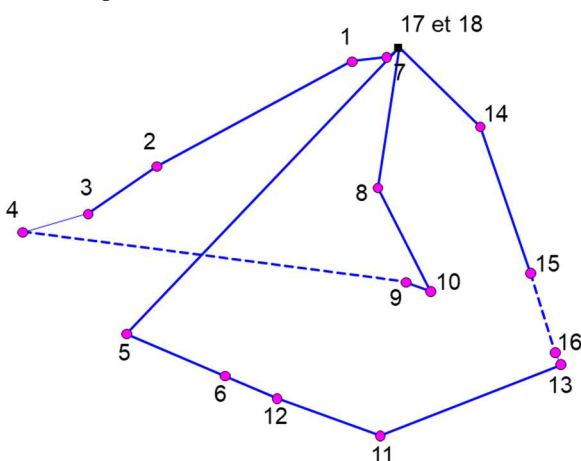


Figure 5: Target network (open line : 4-9 and 15-16)

Results for the AI planning module

The AI planner finds the 20 actions depicted in Figure 6 in 0.004 seconds to move from the initial network to the target network.

```
(add_opeline p18 s8)
(add_opeline s5 p17)
(add_opeline s1 s7)
(add_opeline s13 s11)
(change_switch_connection s11 s13 s10)
(remove_opeline s10 s11)
(change_switch_connection s5 p17 s4)
(remove_add_opeline s5 s4 s9)
(change_switch_connection s1 s7 p18)
(remove_opeline s1 p18)
(change_switch_connection s8 p18 s7)
(remove_add_opeline s7 s8 s10)
(change_switch_connection s10 s8 s9)
(change_switch_connection s9 s10 s8)
(remove_opeline s9 s8)
(change_switch_connection s12 s6 s11)
(change_switch_connection s11 s12 s13)
(change_switch_connection s13 s11 s10)
(remove_opeline s10 s13)
(change_switch_connection s16 s13 s15)
```

Figure 6: List of actions – output of the AI planning module

The legend used is as follows: « s » refers to secondary substation et « p » to primary substation.

- add_opeline si sj: addition of a line with a normally open switch between substation i and j. The cost of this action is therefore 512 k€.
- change_switch_connection si sj sk: a normally open switch is reallocated to another location while maintaining the radiality and n-1 conditions. Line i-j is open/close and line i-k is close/open. The cost of this action is 0k€.
- remove_opeline si sj: the open line between substation i and j is removed. The cost of this action is 0 k€.
- remove_add_opeline si sj sk: a line with a normally open switch is removed and simultaneously a line with a normally open switch is built while maintaining the radiality and n-1 conditions. Line i-j is removed and the open line j-k is added. The cost of this action is 512 k€.

Results for the post-processing module

Each action proposed by the AI planner respects the n-1 condition. However, this is not the case for the voltage profile. Indeed, if the two lines to be reinforced are not carried out upstream, then only actions 1 to 8 can be carried out one by one, and actions 9 to 20 cannot be carried out without having to reinforce the lines. Thus, there are several options for the DSO:

- Case 1: to reinforce from the beginning and thus have 20 intermediate networks that can be planned whenever he wants;
- Case 2: to build the first 8 intermediate networks and then reinforce and perform the additional actions.

Figure 7 shows the intermediate networks for the 8 first

actions.

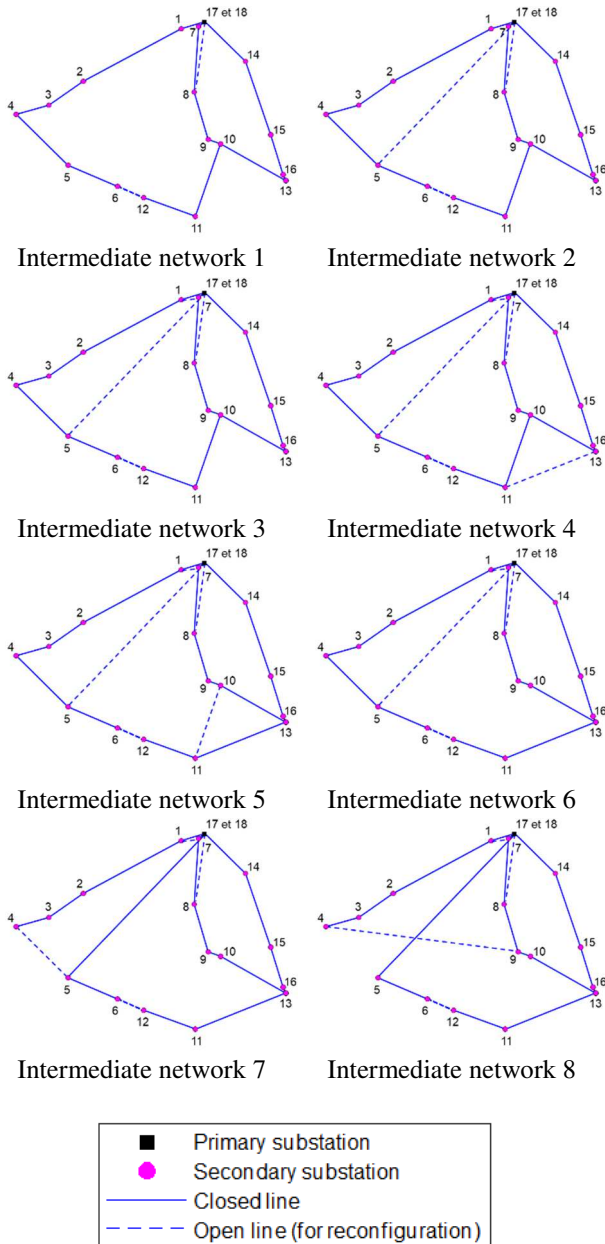


Figure 7: 8 first intermediate networks for case 2.

CONCLUSION AND PERSPECTIVES

The interest of the AI planning is to provide a plan of actions in a very short time. To demonstrate the potential of this kind of approach, in [10], with a simple example, the AI planner provided a solution plan in 0.07 seconds whereas an expert in power systems took one hour. Our approach solves an even harder problem in 0.004 seconds. Nevertheless, the AI planner used have no guarantee of optimality, but it is sound and complete. Also, by constraint, PDDL modelling is purely local, i.e., the conditions of application of an action and its effects can only involve the actors of the action. Then, on bigger and

more complex networks, our proposed PDDL domain as it is, may not be sufficient to always enforce all DSO rules. This claim can be tamed by the fact that AI planning post-processing could easily repair a slightly deficient plan. Thus, a scalability study has to be done in further work. Finally, since we work in a critical application, AI planning must be taken as a decision-support that must be analysed and validated by the DSOs.

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