MULTI-YEAR OPTIMAL PLANNING OF ACTIVE DISTRIBUTION NETWORKS

Gianni CELLI, Susanna MOCCI, Fabrizio PILO
University of Cagliari – Italy
pilo@diee.unica.it

Danilo BERTINI, Rocco CICORIA, Sergio CORTI
CESIRICERCA – Italy
rocco.cicoria@cesiricerca.it

ABSTRACT

The opportunities deriving from the innovative operation of the distribution systems have been underlined in the Literature and might be useful to accomplish economic, environmental and reliability targets by overcoming the existing barriers to innovation and liberalized market. However, despite such widely accepted conclusions, there is still the lack of methods and tools to help Distribution System Operators (DSO) guide the transition from present distribution systems to the future ones. Furthermore, DSO are well conscious that the transition will necessarily be a step-by-step procedure lasting for several years and claiming for a careful optimization of investments. The paper aims at addressing such crucial questions by using a network planning methodology based on the principle of dynamic programming. In particular, the optimal multi-year development plan of active distribution networks is found by solving a suited set of one-stage problems. Such methodology can be applied under the assumption of saving investments from one year to the successive. The solution of the planning problem gives the yearly network evolution in the study period that minimizes the capital and operational expenditures (CAPEX&OPEX). Real-world examples are provided to illustrate the effectiveness of the multi-year planning methodology for active distribution networks.

INTRODUCTION

The function of the active distribution network is to efficiently link power sources with consumer demands, allowing both to decide how best to operate in real time. The level of control required to achieve this is much greater than in current distribution systems. It includes power flow assessment and voltage control, and innovative protections. Furthermore, it requires cost-competitive technologies as well as new communication systems with more sensors and actuators than presently in the distribution system. The increase in required control leads to a dramatic rise in information traffic derived from status and ancillary data. Along with the ability to re-route power, this means that the active network represents a step towards the internet-like model. Undeniably, the process towards the SMARTGRIDS will take many years and there is the need of methods and tools to help distribution planners guide the transition from the existing distribution systems to the future ones [1]. The transition will necessarily be a step-by-step procedure lasting for several years and claiming for a careful optimization and scheduling of investments. In this sense, there is a strict demand for efficient planning tools

that enable maximal utilization of existing capacities in distribution network, i.e. finding a way to work around operational limitations, which is one of the most important features of active distribution networks with significant amount of distributed generation installed. The main difficulty in developing a high quality planning tool is the dimension of distribution networks and the fact that this problem is highly constrained, often with mixed integer variables. Necessity to include dynamic in solving planning problems makes it even more complex. For solving planning problems, several approaches are used: 1) optimization methods; 2) heuristic methods; 3) artificial intelligence (AI) based methods. Optimization methods can converge to the global optimal solution. However, such methods can difficulty be applied to real-size networks because of convergence problems, the computing burden and, most important, the obstacles to take into consideration all the technical constraints. The heuristics algorithms can obtain "good" solution for real size problems and, even if the global minimum cannot be certainly reached, the quality of the solution provided is often acceptable compared to the accuracy of input data. Finally, although AI methods have several advantages (they are robust, flexible, do not require "well behaved" objective functions, can be easily applied for multi-objective optimization), they do not provide any assurance that the best solution will be found and do not handle constraints well. In the paper a heuristic approach is used to solve the optimal multi-year planning of a given distribution network. The dynamic of the optimization is taken into consideration by resorting to the application of dynamic programming. Indeed, it is not feasible to solve a multi-year optimization problem with a fully dynamic approach because distribution networks have normally thousands of customers. Thus, the optimal multi-year development plan of an active distribution system can be found with a reasonable computing burden only by solving a suited set of one-stage problems. By selecting the set of network reinforcements needed in the year t as a subset of the set of the reinforcements in the year $(t+1)$, the adoption of the Bellman optimality principle allows and justifies the reduction of the multi-stage problem to a set of one-stage optimization problems [2]-[4]. Each one-stage optimization problem has been solved with the software package SPREAD developed by the authors. SPREAD allows the optimal planning of MV distribution networks with DG, taking into account expansion over time and usual technical constraints [5],[6]. The heuristic optimization algorithm minimizes the generalized cost of the network constituted by the CAPEX (investments for new lines, the revamping of existing lines and primary substations, and network automation) and the OPEX (e. g. losses and maintenance).

The optimal solution has to comply with several technical constraints on the voltage profile, the maximum exploitation of assets, the quality of service, etc. The random behaviour of both distributed generation and loads is fully considered with the adoption of a probabilistic load flow. Radial or meshed networks with trunks and laterals in scenarios with several hundreds of nodes in a reasonable computing time can be studied [6]. One of the most important feature of SPREAD is that the planning actions available to solve network problems like poor voltage regulation or excessive power flows are not only based on the building of new lines or on network topology modifications, but also on the application of the control actions typical of active networks.
 The solution of the planning problem gives the yearly network evolution in the study period that minimizes the sum of CAPEX and OPEX. Real-world examples are provided to illustrate the effectiveness of the multi-year planning methodology for active distribution networks.

DYNAMIC PROGRAMMING

Dynamic Programming (DP) is an approach developed to solve multi-stage decision problems and is based on the well-known Richard Bellman's Principle of Optimality: "*An optimal policy has the property that no matter what the previous decisions have been, the remaining decisions must constitute an optimal policy with regard to the state resulting from these previous decisions*" [2]. Actually, this approach is equally applicable for decision problems where multi-stage decision making is not in the nature of the problem but is induced only for computational reasons. DP tends to break the original problem into sub-problems and finds the best solution of the sub-problems, beginning from the smaller in size. When applicable, DP dramatically reduces the runtime of some algorithms from exponential to polynomial.
DP can be successfully applied when:
- the problem can be divided into stages and a decision is required at each stage,
- a finite number of states is associated with each stage,
- the decision at one stage transforms one state into a state in the next stage,
- there exists a recursive relationship that, provided that the states at stage $j-1$ are known, identifies the optimal decisions to reach the states at stage j
- the recursion for determining the optimal decisions at the stage j only depends on the states at stage $j-1$ and not on the way these states have been reached.

Fig. 1 depicts a possible implementation of DP. The problem has been subdivided into a sequence of decisional levels (stages) D_I, D_{II}, ..., D_n. The states of the system α, β, ..., η may be reached with different sets of decision. In Fig. 1 each state is labeled with a function L that considers the previous stage and the arriving state. In order to clarify the process let suppose that state β at the D_{II} has to be reached from D_I. Possible states in D_I are α, β, γ, and …η, each one labeled
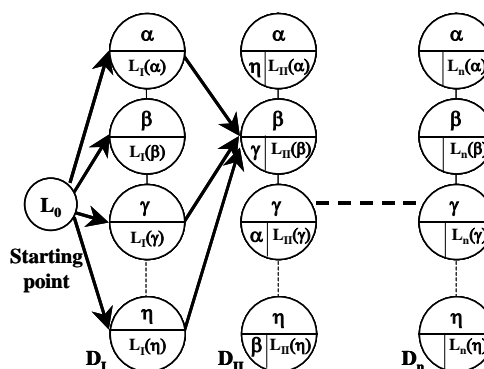

Fig. 1: Schematic flow chart of Dynamic Programming

with the optimal value of the cost function. For instance, the label $L_{II}(\beta)$ of β is the minimum value of the cost function calculated considering the couples formed with β and the remaining available candidates (in Fig. 1 the optimal path to β has been assumed through γ).
By repeating this procedure for all the states at the D_{II} stage, the optimal policy that allows reaching the D_{II} can easily be found. The optimal policy corresponds to reach the state in D_{II} with the smallest label but, it is worth to noticing that all the states in D_{II} are reached with an optimal policy. By so doing, each policy to reach D_{III} from D_{II} necessarily contains optimal sub-policies and the Bellman's Principle will be satisfied. In the following section, the application of DP to the multi-year planning of distribution networks will be deeply discussed with some examples.

MULTI-YEAR PROGRAMMING

The distribution network planning aims at defining the expansion and the reinforcements that are necessary to face the natural rise of energy demand, the connection of new customers and Distributed Generation. Furthermore, the implementation of active management that involves network automation, load response, and the dispatching of active and reactive power generated by DG may also require investments. Finally, the goal of planning is to minimise the sum of CAPEX and OPEX during a given time period. Naturally, an economic sound solution has to comply with several engineering constraints e.g., on the voltage profile, the maximum exploitation of feeder capacity, the maximum allowable customer minute loss (CML), the maximum allowable frequency of interruptions, etc.. The software package SPREAD allows finding the optimal network expansion planning considering only single stage optimizations (i.e., the building of new lines, or the revamping of the existing ones, starts at the beginning of the study period or when a new primary substation is built).
SPREAD allows solving the optimal planning of a given network, the optimal siting and sizing of DG taking into consideration the random behaviour of loads and generators, uncertainties in the DG power production as well as the

opportunities related to the implementation of the active management of distribution systems [5],[6]. In order to overcome the limitations caused by the single-stage optimization, particularly significant with DG and active management, a novel multi-year optimization algorithm is proposed in the paper.

The multi-year planning aims at finding the optimal development of a given distribution system by means of the run of a prefixed number of single stage optimizations (the number of single stages depends on the subdivision of the time period considered). What is worth to noticing is that the non-linear nature of the problem does not assure that single stage optimizations are optimal sub policies that are fundamental for the application of the Bellman's Principle. This fact means that the simple succession of static optimizations does not necessarily lead to the global optimum and in many cases all the possible combinations of static optimization has to be considered.

In order to clarify these concepts, let consider a dynamic optimization spanning on a period of n years (or n sub-periods lasting for more than one year). The starting point, PSt_0, is the network at the beginning of the planning period (Fig. 2). The network at the time horizon j, PSt_j, is achieved with a set of optimal choices (e.g., building of new lines, upgrading of existing lines, etc.) that is the result of a one stage planning scenario. Starting from the PSt_0, the final goal of the dynamic programming is to define the optimal sequence of subpolicies $PSt_1,…, PSt_{n-1}$ to optimally reach the final planning design at the horizon year. Three different situations may be the result of the single stage optimizations:

1. the optimal network for year j is included in the optimal network for year $j+1$ for $j=1…n$. That means that all the reinforcements that are necessary in the time period between the starting year and j are all strictly included in the $j+1$ optimal network ($PSt_1 \subset PSt_2 \subset ... \subset PSt_n$),

2. the previous statement is fulfilled for only first m years in the planning horizon i.e., the set of reinforcements and enhancements obtained for the first m years is common for all years that follow year m ($PSt_1 \subset PSt_2 \subset ... \subset PSt_m \not\subset PSt_{m+1} \not\subset ... \not\subset PSt_n$),

3. neither of previous statements are fulfilled ($PSt_1 \not\subset PSt_2 \not\subset ... \not\subset PSt_n$).

In the first case, the optimal solution of the n-year planning problem is constituted by the sequence of the one-stage planning solutions. In the second case, the optimal solution till the m year is the sequence of the first m one-stage optimization whereas in the remaining $n-m$ the optimal solution can only be achieved by applying the DP as it is
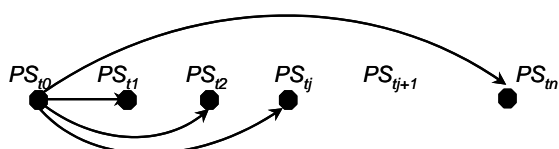

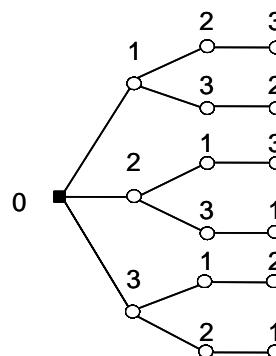Fig. 2: One–stage planning scenarios

Fig. 3: Decision tree for the application of DP in a 3-years optimization

necessary whether the solutions fall in case 3) [7], [8]. The DP can be easily explained with a simple example applied on a study period three years long. The *decision tree* depicted in Fig. 3 shows all the possible combinations of one-stage optimizations. Each node in the *decision tree* represents a possible solution of a single stage optimization. A sequence from the root to a leaf is a solution for the multi-stage optimization. Different solutions are achieved with different temporal sequences. The number of possible combinations that have to be examined is equal to *n!* if *n* is the number of years in the planning horizon. In order to clarify the model three of the six solutions are described in the following:

▪ Solution (0, 1, 2, 3), called *forward fill-in.* The problem is initially solved in the period 0-1 (PSt_1) and gives the set of planning action that are necessary in the first year. Then, starting from PSt_1, the optimal network for the second year is found by assuming as available all the actions performed in the first period. Finally, by assuming the PSt_2 as the new starting point, the PSt_3 is found. The sequence formed by {PSt_1, PSt_2, PSt_3} is a multi-stage planning scenario and a possible solution of the 3-years planning problem. Necessarily, by construction, $PSt_1 \subset PSt_2 \subset PSt_3$ and the solution of the *forward fill-in* is the sequence of the three intermediate solutions (optimal sub-policies).

▪ Solution (0, 3, 2, 1): called *backward pull-out.* In this case preliminarily the PSt_3 optimization is performed to find the optimal network at the end of the planning period starting from the PSt_0. The second step is the identification of PSt_2 with an optimization that can only consider actions included also in PSt_3 (i.e., $PSt_2 \subset PSt_3$ by construction). Finally, PSt_1 is found by limiting the planning actions to those that are included in PSt_2 (i.e., $PSt_1 \subset PSt_2$ by construction). The examined path leads to another possible solution of the 3-years planning problem.

▪ Solution (0, 2, 3, 1): preliminarily the optimal network at the end of year 2 PSt_2 is found with a single stage optimization from PSt_0. Then the optimization is performed in the last period (2-3) by assuming that all the planning actions of PSt_3 have to comprise PSt_2

(again $PSt_2 \subset PSt_3$). Finally, by considering that all the network reinforcements and expansions at the end of year 1 are available in the period 1-2, all the set of actions in PSt_1 has to be contained in PSt_2 (again $PSt_1 \subset PSt_2$).

Once all the paths in the graph of Fig. 3 are assessed, all the possible *multi-year planning scenarios* are known and they can be compared to find the most convenient one. The multi-year planning scenario with the minimum cost (all the solutions have to comply with technical and economical constraints) represents the optimal choice.

RESULTS AND DISCUSSION

In order to show the effectiveness of the proposed methodology, a small portion of an actual Italian distribution network has been used. This network is constituted by 2 HV/MV substations and 60 existing MV/LV nodes, divided into 18 trunk nodes and 42 lateral nodes, with a global peak power demand of about 10 MW. The period taken into consideration for the planning study is 15 years long (from 2010 to 2025), subdivided into 3 sub-periods lasting for 5 years. The distribution network is on a rural area, so all the branches are of the overhead type. For each MV/LV node a constant power demand growth rate of 3% per year has been assumed. The two main feeders have been assumed existing at the beginning of the study period with a cross-section of 70 mm^2, while all the laterals have to be built. The dynamic evolution of the network has been studied considering the appearance of a new load of 1 MW (node 63) at the beginning of the second sub-period (year 2015), and a new gas turbine generator of 1 MVA (node 64) at the beginning of the last sub-period (year 2020).

As described in the previous section, the three single stage optimizations have been performed (Fig. 4), starting from the existing network and varying the planning horizon at the end of each sub-period. As it can be observed from the three network arrangements, each solution is not strictly included in the following one, thus it is necessary to analyze all the possible combinations derived by the decision tree (Fig. 3), in order to find the optimal multi-year planning scenario.

Table I: Multi stage planning scenario costs.

	CAPEX [k€]	OPEX [k€]	Total Cost [k€]
case 1	1014.8	1364.4	2379.2
case 2	1018.6	1276.6	**2295.2**
case 3 & 4	1028.3	1359.8	2388.1
case 5 & 6	1061.4	1246.6	2308.0

The six different temporal sequences examined are:
Case 1 – *forward fill-in* 1-2-3;
Case 2 – optimization 1-3-2;
Case 3 – optimization 2-1-3;
Case 4 – optimization 2-3-1;
Case 5 – optimization 3-1-2;
Case 6 – *backward pull-out* 3-2-1.

Among these solutions, only four different multi stage scenarios have been obtained. In fact, case 3 is equal to case 4 and case 5 is equal to case 6. The overall costs of the network for these scenarios are reported in Table I, whereas the final network configurations are depicted in Fig. 5, except for the cases 5 and 6 which lead to the same final network topology depicted in Fig. 4c. For each scenario, the network evolution in the whole planning period can be derived from the relative figure, by considering the load connected to the network at year 2015 and the generator at year 2020, whereas all the laterals are built at the beginning of the study period (2010). All the new branches have a cross-section of 25 mm^2.

The best planning solution with the minimum sum of CAPEX and OPEX is the one obtained in the second case. It is worth to noticing that the classical *forward fill-in* multi-year planning solution is not the best one, as it happens in many cases. This consideration confirms the importance to have suitable planning tools, like that proposed in this paper, able to help the planner in its difficult task.

CONCLUSIONS

The distribution system is going to be radically modified according to the SMARTGRIDS concept. Many significant benefits are expected for the environment, the economy, the quality of service and the energy market. Undeniably, the
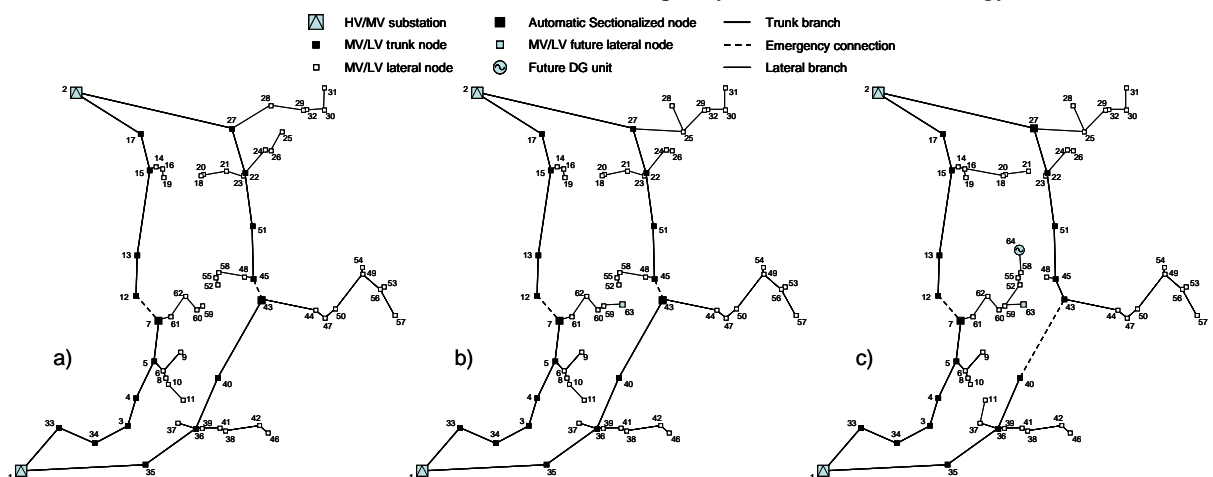

Fig. 4: Single stage optimizations with planning horizon at 2015 (a), 2020 (b), and 2025 (c)

transition from the present to the future distribution will take a long time and require massive investments. For these reasons, tools for the optimal medium-long term system planning are necessary in order to cope budget limitations with the optimal allocations of resources and priorization of investments. In the paper an optimization algorithm for the optimal multi-year planning of active distribution systems is presented. The algorithm, implemented in the professional planning software SPREAD, allows finding the optimal sequence of investments in real size distribution systems considering as planning actions not only network topology changes, network upgrading and expansion but also the opportunities from the active management of the system. The real world example shows the effectiveness of the procedure, and highlights that the optimal sequence of investments in long term planning it is not generally formed by a sequence of single-stage optimal solutions, especially whether DG and active management is considered.

ACKNOWLEDGEMENT

REFERENCES

[1] European Commission, 2006, "European Smartgrids Technology Platform - Vision and Strategy for Europe's Electricity Networks of the Future", *Available: http://europa.eu.int/comm/research/energy* .

[2] R. Bellman, 1957, *Dynamic Programming*, Princeton University Press.

[3] J. Hartman, 2004, "An overview of Dynamic Programming", Coral Seminar series. *Available: http://coral.ie.lehigh.edu/.*

[4] Kaufmann, 1972, *Méthodes et modéles de la recherché opérationnelle*, Volume II, Paris, Dunod, pp.83-171.

[5] V. Allegranza, G. Celli, R. Cicoria, S. Mocci, F. Pilo, 2003, "An Integrated Tool for Optimal Active Network Planning", *Proc. of CIRED Conference*, Barcelona, Spain, 12-15 May 2003.

[6] G. Celli, S. Mocci, F. Pilo, R. Cicoria, 2002, "Probabilistic Optimization of MV Distribution Network in Presence of Distributed Generation", *Proc. of PSCC Conference*, Sevilla, Spain, 24-28 June 2002.

[7] Z. N. Popovic, D. S. Popovic, 2005, V. Dj. Kerleta, "A novel methodology for multi-year planning of large scale distribution networks", *Proceedings of CIRED Conference*, Turin, 6-9 June, 2005.

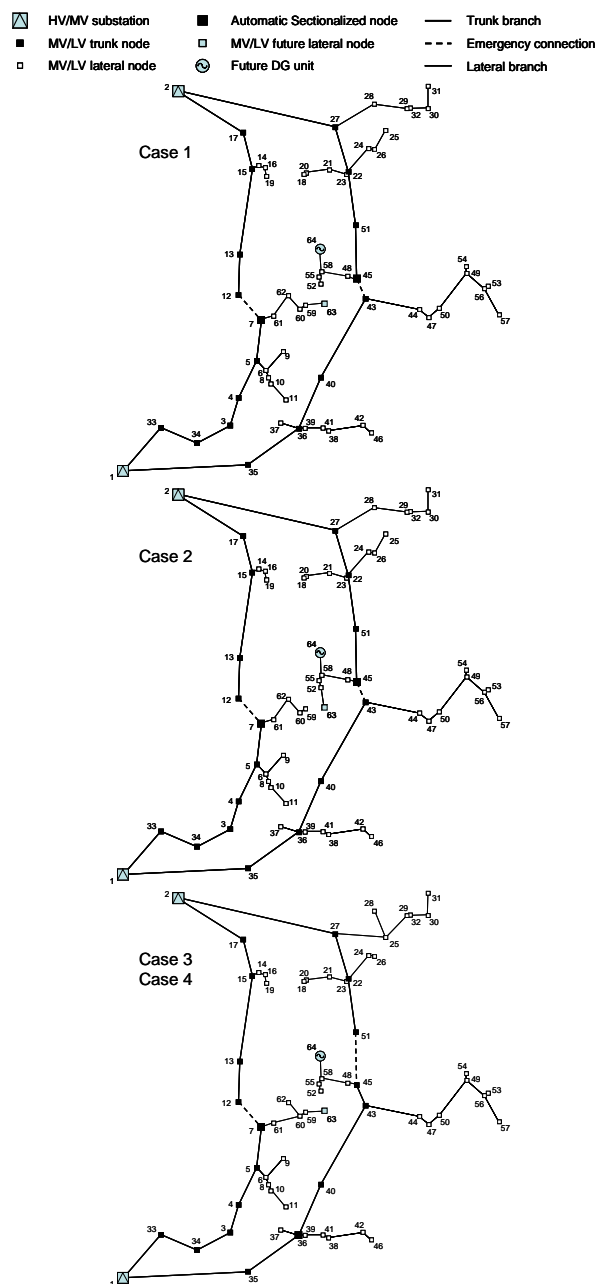[8] H.L. Willis, 1997, *Power Distribution Planning Reference Book*, Marcel Dekker Inc., New York, USA.

Fig. 5: Final network configurations for different scenarios