MULTI-OBJECTIVE ANALYSIS OF REGULATORY FRAMEWORKS FOR ACTIVE DISTRIBUTION NETWORKS

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ABSTRACT

An important step towards Smart Grid are the Active Distribution Networks, based on controllable loads, generators and storage devices to reduce the DERs impact on the distribution systems. System stakeholders have conflicting goals and the application of the multi-objective optimization allows finding the best solutions for each of them, highlighting the relationship between the regulatory environment and the level of active networks implementation. Active operation can help solve the tensions caused by the contrasting goals of investors and DSO's, direct consequence of the regulatory mechanism adopted. The main novelty of this paper is the adoption of advanced level of implementation for active management.

INTRODUCTION

The liberalization of the energy market, technological innovations and a growing tendency towards sustainable development are major drivers for the integration of Distributed Energy Resources (DER). The increased interest in renewable energy and local production of heat and electricity, combined with storage and demand-side participation, will result in a significant change in distribution system. However, the limited controllability, restricted to curtailment and reactive power control if applied, and the overall low capacity factor of renewable energy sources could demand significant transmission and distribution grid reinforcements. Moreover, while much of the technical and political discussion about how to ensure a sustainable energy future focuses on energy efficiency, renewable energy sources, storage, and plug-in electric cars, it is often forgotten or underemphasized that these solutions all depend on a smarter grid to achieve scale and cost effectiveness. The electric network of the future – the Smart Grid (SG) - will be internet like in the sense that decision-making will be distributed and with bi-directional communication and power flows [1-3]. In the short term, the Active Distribution Networks (ADNs), based on controllable loads, generators and storage devices to reduce the DERs impact on the distribution systems, will incorporate some of the features of the SG and will be an intermediate step towards SG [4]. Continuing the recently works of the authors, a Multi-Objective (MO) optimization, based on the NSGA-II, has been implemented in order to find the Pareto-set of DG placements in some scenarios characterized by different regulatory frameworks, level of active management and incentive mechanisms [5-9]. The Civil Society (CS), the Distribution System Operators (DSOs) and the DG owner (investors) are the players considered. The CS is mainly interested in preserving the environment and it favorites the DG and the integration of Renewable Energy Sources (RESs) at reasonable costs. The DSO strives to minimize OPEX related to the distribution services. The minimization of investments might also be a DSO's goal due to budget restrictions or financial costs. Finally, DER investors also make decisions considering their CAPEX and OPEX, the connection costs, and use of systems charges. Moreover, incomes from energy selling and incentives for RES are the main goals of DER investors. System stakeholders have conflicting goals and the application of the MO optimization allows finding the best solutions for each of them, highlighting the relationship between the regulatory environment and the level of ADN implementation. The active operation can help solve the tensions caused by the contrasting goals of investors and DSO's, which are a direct consequence of the regulatory mechanism adopted.

The paper aims at showing the impact of ADN implementation level on the development and integration of DER in the system. Different scenarios have been assumed and the behavior of the system stakeholders has been simulated with an MO algorithm so that each of them tries to achieve the maximum benefit.

The main novelty of this paper is the simulation of advanced ADN schemes. The network reconfiguration is profitably exploited to minimize the resort to the DERs (generators and/or loads), particularly if they are renewable energy based and the control action leads to a power generation reduction. The demand side integration is also exploited to make the demand following the generation in opposition to the classical paradigm with the generation that follows the load. Finally, DER is treated as an active subject of the system available to give the system services like reactive power, spinning reserve. All scenarios have been tested on a real case study.

PLANNING OPTIMIZATION ALGORITHM

The MO optimization implemented in the paper is based on the NSGA-II. This algorithm, introduced by Deb to overcome some critics moved against its first proposal, is recognized as one of the most efficient MO Evolutionary Algorithm (MOEA). The NSGA-II algorithm sorts a population into different non-dominated levels (Pareto-optimal solutions) [5-9].

Coding of a solution

If the network structure is fixed, all the branches between nodes are known, and the evaluation of the objective functions depends only on size, type, and location of DG units. For this reason, each solution can be coded by using a vector, whose size is equal to the number of MV/LV nodes, in which each element contains the information on the presence of a DG unit [5, 6].

Case Study

The case study has been formed by merging portions of different real distribution networks (Fig. 1). In order to limit the computational effort without losing the general validity of the example, the existing MV/LV nodes has been clustered and reduced to 15 trunk nodes and 21 lateral nodes, equivalent to 16 MW load. The network is constituted by three existing open loop feeders with overhead and underground sections. The three open loop trunk feeders connect the three primary substations in the area. Several overhead laterals allow supplying the most peripherical loads. The network delivers energy to rural and urban areas: therefore, customers are represented by different daily load profiles, considered in the algorithm. Because of the load growth, voltage drop problems are to be expected in the network in some load/generation combinations. The algorithm relieves the constraint violations by resorting to the active management of the network, if available. If a contingency cannot be relieved with the ADN management, then the procedure disposes the opportune network upgrading.

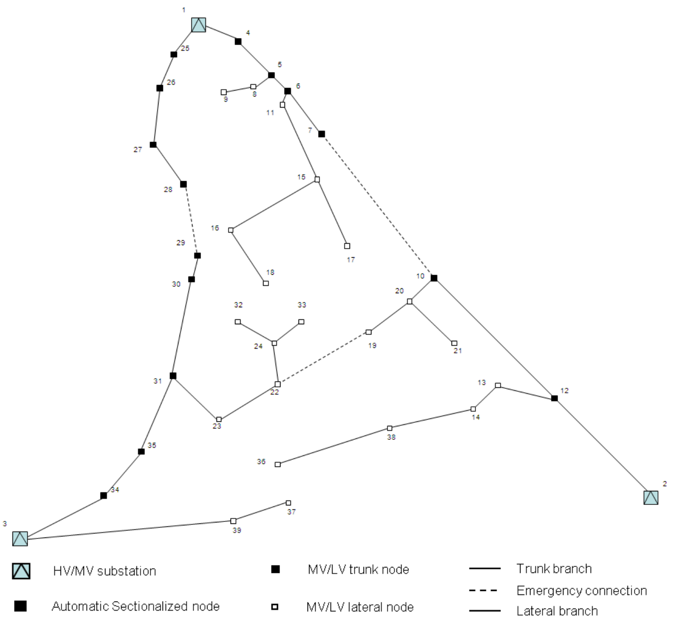

Fig. 1 – Case Study

In the MO optimization the following rated sizes are considered for RES: 1000 kVA, 3000 kVA and 6000 kVA wind turbines, 500 kVA photovoltaic generator, 1000 kVA and 5000 kVA biomass units. The planning period is of 5 years, whereas the technical life of every generation technology is equal to 15 years.

Definition of scenarios

In the paper, some possible different scenarios have been assumed (Table I). The Scenario A, based on the present Italian regulation, is based on the *"connect and forget"* policy with no control of DER by the DSO and no use of system charge. The network investments made by the DSO are partially refunded by the Regulator. In the Scenario A a "full" incentive mechanism has been adopted to promote the integration of RES. According to the Italian legislation, RES earn Green Certificates as a function of the energy produced (1 Green Certificate = 100 €/MWh). PV generation has a special treatment as the energy produced by PV is bought at a special price as high as 300 €/MWh, but it cannot earn Green Certificates. In the other scenarios different levels of active management have been implemented.

TABLE I
DEFINITION OF THE DIFFERENT REGULATORY SCENARIOS.

Scenario	ADN implementation	Investor responsibility	Use of system charge
A	no	no	no
B.1	GC (P)	committed	Energy curtailed
B.2	GC (P)	remunerated	no
C.1	DG Control (P&Q)	committed	Energy curtailed
C.2	DG Control (P&Q)	remunerated	no
D	DSM	remunerated	no
E	RCF	no	no
F	DG Control+DSM+RCF	remunerated	no

Scenarios B.1 and B.2 are based on the Generation Curtailment (GC) to relieve system contingencies. In the case B.1, each DG unit has to accept a maximum amount of energy curtailment per year as a sort of "*use of system charge*", whereas in the Scenario B.2 investors may decide to help the DSO to manage the network, being paid for the services offered and the sharing of responsibilities.

In C.1 and C.2 scenarios DG fully participates to system operation with active and reactive power. In the scenario D customers participate to the active management by accepting a *Demand Side Management* (DSM) action. In the Scenario E the on-line reconfiguration (RCF) is applied in order to reduce the network losses. In the scenario F the full control of DG units is remunerated as in the Scenario C.2, and the DSO can also resort to the on-line reconfiguration and demand side integration.

Objective functions

Depending on the scenario, outcomes and incomes are calculated for the three aforementioned players by using the Objective Functions (OF) reported in Table II.

TABLE II
OBJECTIVE FUNCTIONS RELEVANT TO EACH SYSTEM PLAYER.

Civil Society	Distributors	Investors
RES integration (%DG)	Network upgrading net costs $[(1-r_{DSO})\cdot C_U]$	Building and operation costs (C_{DG})
Energy Losses (E_L)	Cost of energy losses (C_L)	Connection cost (C_{Conn})
ADN OPEX (C_{ADN})	Income for ADN management ($I_{ADN} = r_{ADN}\cdot C_{ADN}$)	Incomes from energy production (I_{En})
Asset management ($r_{DSO}\cdot C_U$)	Income from DG (I_{Conn})	Income from Ancillary Services $[I_{AS} = (1-r_{ADN})\cdot C_{ADN}]$
Expenditure for incentives (EX_{inc})		

Referring to the previous considerations, the three players have the following OFs [7].

$$\begin{aligned} OF_{DSO} &= I_{ADN} + I_{Conn} - \left[\left(1-r_{DSO}\right)\cdot C_U\right] - C_L \\ OF_{Inv} &= I_{En} + I_{AS} - C_{DG} - C_{Conn} \\ OF_{CS}^{DG} &= 1 - \frac{\%DG}{100} \\ OF_{CS}^{losses} &= E_L \\ OF_{CS}^{costs} &= C_{ADN} + \left(r_{DSO}\cdot C_U\right) + EX_{inc} \end{aligned} \quad (1)$$

where r_{DSO} is the percentage of refurbishment of the DSO network upgrading costs (C_U).
In this paper the CS point of view has been represented by maintaining three different and heterogeneous OFs, in order to avoid the definition of reference values for these terms.
Investors strive to maximize the RES integration in order to exploit their profits, whereas DSOs are interested in the DERs configuration that maximizes the benefits of the distributed generation in the distribution network (e.g. Joule losses reduction, minimization of network upgrading investments). The Regulator has to guarantee the system efficiency by supporting the higher RES integration at reasonable cost, connected to the incentive policy offered to the producers.

RESULTS AND DISCUSSIONS

The results of the active network scenarios are summarized in Table III. In the Scenario A (no control of DER by the DSO and no use of system charge), the incentive mechanism adopted promotes the integration of RES (140%), and the payback time (PBT) of the investment is very short (1.8).
As described before, in the Scenarios B the DG owners accept the control of the active power (P in Table I) in order to help the DSO to relieve voltage and current constraint violations. In scenarios C, the DG control is also on the reactive power produced by DG (P&Q in Table I).
In B.1 (C.1) the DER investor accepts a maximum amount of energy curtailment per year (mandatory and not remunerated) as a sort of "*use of system charge*", whereas in B.2 (C.2) producers may decide to actively participate to system operation, being paid for the service offered (remunerated). It can be noticed that all the ADN scenarios allow a higher DER integration compared with the scenario A (30% more roughly). In particular, the DG reactive power control allows the highest DER integration (175%) and high incomes to the investors. In fact, by considering a fixed DER configuration and changing the DG power factor, the same result can be obtained with a lower reduction of the active power P, which permits the RES incentives. It should be recognized that in this case the power converters are to be over designed with an increment of capital expenditures. Scenario B.1 (C.1) seems a good compromise solution for the three stakeholders. Against a limited reduction in the DER investor incomes a significant cut in the CS costs is obtained.
By resorting to the DSM in Scenario D and to the RCF in scenario E, the network upgrading costs are reduced in comparison with the referring Scenario A.
Scenario D is similar to scenario A (due to the small DSM actions) and presents DG units very spread in the distribution network: such DER configuration permits the system contingencies reduction as with the DSM implementation, but with the saving due to the absence of any additional cost.
Results obtained in Scenario F with the full control of DG units, the DSO resort to the on-line reconfiguration and demand side integration permits merging all the advantages derived from the active network management.

CONCLUSIONS

The main novelty of this paper is the simulation of advanced ADN schemes, by highlighting the relationship between the regulatory environment and the level of active management implementation. The paper shows the impact of ADN implementation level on the development and integration of DER in the system. Different scenarios have been assumed and the behavior of the system stakeholders has been simulated with an MO algorithm so that each of them tries to achieve the maximum benefit.
The main relevant conclusion is that the active operation of the system is fundamental to reduce investments for the network upgrading in the medium term limiting the barriers to the integration of renewables. Moreover, the ADN allows finding the good compromise solutions for the distribution system stakeholders (Civil Society, DER investors and DSOs). In other terms, the active management permits

TABLE III
AVERAGE VALUES IN THE OPTIMAL PARETO SETS OF THE OFS AND OF SOME SIGNIFICANT PLANNING PARAMETERS.

Regulatory environment		Scenario A	Scenario B.1 (remunerated)	Scenario B.2 (committed)	Scenario C.1 (committed)	Scenario C.2 (remunerated)	Scenario D (DSM)	Scenario E (RCF)	Scenario F (P&Q+DSM+RCF)
OF_{DSO} [M€]		1.4	0.6	1.1	0.6	1.2	1.3	1.3	0.9
OF_{Inv} [M€]		51.1	33.6	37.5	37.3	38.6	53.6	50.5	41.2
Civil Society (costs) [M€]		4.1	13.8	16.7	14.7	17.3	4.8	4.2	13.8
DG penetration		140 %	174 %	171 %	175 %	171 %	145 %	139 %	171 %
Net DSO CAPEX [k€]		9.5	34.2	34.2	33.7	34.6	4.9	6.6	6.2
E_L [MWh]		2.52	6.76	5.80	6.70	5.13	2.67	2.68	6.19
PBT (mean value) [years]		1.8	2.0	2.1	1.9	2.0	1.8	1.7	2.0
Wind plants	avg. power	2794 kVA	3751 kVA	3468 kVA	3889 kVA	3835 kVA	3121 kVA	2572 kVA	3493 kVA
	avg. number	10	8	9	8	9	10	12	9
Photovoltaic plants	avg. power	377 kVA	442 kVA	382 kVA	433 kVA	438 kVA	417 kVA	370 kVA	384 kVA
	avg. number	2	2	2	2	2	2	2	2
Biomass plants	avg. power	167 kVA	3519 kVA	3500 kVA	3491 kVA	3417 kVA	-	167 kVA	3167 kVA
	avg. number	1	1	1	1	1	-	1	1

balancing the advantages and disadvantages to the system players related to a higher DER integration in the distribution network. The Scenario without active management remuneration is preferable, because the reward penalizes too much the Regulator whereas the lower income obtained by DER investors in scenarios characterised by no compensation for the DER active management is still acceptable.
Finally, the active distribution network implementation contributes to reach a high DER integration in the distribution system.

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