Assessing the Impact of Incentive Regulation for Innovation on RES Integration

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***Abstract*—Investing in innovative Smart Grids (SGs) technology can reduce overall investments in distribution systems with unpredictable renewable energy sources (RES). Regulators should, therefore, decide what incentives are desirable and design a flexible economic regulatory framework able to encourage distribution system operators (DNOs) to decide for innovation in the SGs. An innovative method that can support the regulators in encouraging RES exploitation by determining the right incentives to favor investments in innovation in an electrical distribution network is proposed in this paper. The method allows stakeholders like regulators, distribution companies and developers evaluating the long-term economic effects of their decisions. The effectiveness of the proposed method, based on non-dominated sorting genetic algorithm (NSGA-II) and on multi-period optimal power flow (MP-OPF), is verified on an 84-bus network.**

***Index Terms*—Power distribution, power system economics, power system management, power system planning, power system simulation, smart grids, wind energy generation.**

NOMENCLATURE

Acronyms

RES	Renewable energy sources.
DNO	Distribution network operator.
SGs	Smart Grids.
R&D	Research and development.
NPV	Net present value.
NSGA-II	Non-dominated sorting genetic algorithms.
MP-OPF	Multi-period optimal power flow.
AM	Active management.
WTs	Wind turbines.
DG	Distributed generation.
OPEX	Operational expenditures.
CAPEX	Capital expenditures.
RPZ	Registered power zones.
O&M	Operation and management.
AVC	Automatic voltage control.
OLTC	On-load tap changer.
SCADA	Supervisory control and data acquisition.
RTU	Remote telemetry units.
CF	Capacity factor.

Variables

$\mathbf{y}$	Optimization variable of the NSGA-II.
$\mathbf{x_j}$	Vector consisting of a set of controllable quantities and dependent variables during each period j.

Constants

N_C	Number of candidate locations.
N_T	Number of defined WT types.
r	Interest rate.
N	Planning horizon.

I. INTRODUCTION

A. Motivation

EUROPEAN 2020 target is imposing a significant contribution from renewables and, when looking forward to EU 2050, all electricity should be produced by zero carbon energy sources while coal or gas will only be used with carbon capture and storage. These targets will result in the large-scale integration of renewable energy sources (RES) by distribution network operators (DNOs) that will be forced to deal with challenges related to the power grid balancing due to intermittent RES and, therefore, to expand and improve distribution networks [1]–[4]. In this context, as investments in distribution grids are not adequately encouraged by the current regulatory framework, higher risks of outages, distribution networks congestions, inadequate RES integration and a loss of quality of supply may result. New investments in innovations in electrical distribution grids, if properly incentivized, may allow improving the integration and the exploitation of RES. Two different approaches, specifically the "fit and forget" or the "smart grids" approach can be followed by DNOs. Under either approaches, the optimal integration of RES in distribution grids is essential to guarantee the best use of resources. In order to support large penetrations of RES and avoid congestions [5], [6], the "fit-and-forget" approach would require extremely costly reinforcements in the network, such as investments in additional power transformers

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and distribution lines [7], [8] and generally over-sizing the distribution grid components. This approach, however, determines sub-optimal integration of RES and increased power losses [9]. In the "smart grid" approach, instead, the use of current assets can be optimized avoiding network reinforcement and carrying out investments in information and communication technologies to monitor, control and automate the Smart Grids (SGs) [11]–[13].

Even if a fundamental shift to the "smart grid" approach is desirable [14]–[16] in order to integrate large amount of RES in electrical networks, over the last decades, DNOs have handled limited technological innovation. This mainly focused on reducing operating costs, including expenditure in research and development (R&D), and creating more efficient financial structures. Significant technological innovation is, instead, needed to implement the "smart grid" approach and a regulatory revision of the financing model applied to DNOs by national energy regulators is also necessary in order to promote this technological shift [17]–[20].

Regulators play, in fact, a dominant role in encouraging DNOs to develop the SGs. Many energy regulators do not recognize, indeed, investments in innovation in their regulatory asset base and usually follow a restricted approach by neglecting the motivation for capital expenditure related to SGs in their cost benefit analysis [20], [21]. Even if there are some exceptions, such as a competition-based procedure recently launched by the Italian regulator to incentivize SGs projects and the Low Carbon Networks Fund set up in UK to allocate £500m over the period 2010–2015 for promoting new DNO initiatives for smarter electricity networks, most of regulations in the world are not flexible and focus more strongly on short-term optimization rather than on long-term needs [20]–[26].

B. *Approach*

On the basis of these remarks, new research questions arise for regulators when facing with the innovation incentives and their impact on RES integration. A specific goal in this context consists in supporting the integration of RES in active networks [13] and SGs [14]–[16] by defining the most suitable level of additional incentives for innovation. Accordingly, innovative tools, able to integrate incentive innovation into the regulation design are required.

This paper proposes a method that can assist the regulators in order to facilitate the best integration and exploitation of RES by determining the correct incentives related to investments in innovation in distribution networks. In particular, the implementation of active management (AM) schemes is considered as distribution grid innovation in order to assess their economic impact for developers and DNOs. By using the proposed method it is also possible to assess different options related to RES investments, such as the selection of the site, type and number of new wind turbines (WTs). By comparing the technical and economic performances of passive distribution networks with those achievable after implementing AM schemes it is possible to evaluate the benefits deriving from distribution grid innovation and incentive regulation for innovation.

The method allows considering the distinct preferences of developers and DNOs with regards to RES and WTs related investments. DNOs and WTs developers have different, contrasting objectives: while developers aim at maximizing the net present value (NPV) related to their investment, DNOs aim at maximizing the NPV derived from the incentives. These are mainly received for innovation, RES integration and power losses reduction. A hybrid optimization method is proposed with the aim of assessing both objectives over a planning horizon. The hybrid method makes use of on non-dominated sorting genetic algorithms (NSGA-II) procedure for finding multiple Pareto-optimal solutions in a multi-objective optimization problem and of multi-period optimal power flow (MP-OPF) [7], [8]. NSGA-II is used for selecting the optimal sites and number of WTs among some selected types. MP-OPF, integrating AM schemes [11], [13] and considering the time-varying characteristics of the load demand and wind generation is used to evaluate wind energy generation and energy losses. In order to evaluate the relative benefits and costs of different investments in the SGs made by DNOs and WTs developers, the proposed method also considers the costs related to the AM implementation in different scenarios. The method is also applicable to other types of RES although the analyzed case studies concentrate on WTs.

C. *Innovative Contributions*

The proposed method, including incentives for innovation, can support the regulator in defining the correct incentives to stimulate a better RES penetration and integration in active distribution networks. Thanks to the proposed method, the regulator is able to design a flexible economic regulatory framework with the objective to stimulate the DNO in making the best investments in AM schemes. By using the proposed method, the distribution companies can have an overall vision on the development of the business situation in the electricity sector and can assess their outcomes in the considered regulation scheme. On the other end, WTs developers may also use the method in order to assess the long-term economic effects of their investment decisions.

Even if many previous researches have already been carried out on distributed generation (DG) and RES planning problem [7], [8], there are, to the author's knowledge, no studies that recommend methods to evaluate the effectiveness of a regulatory framework including incentives for innovation to contribute to RES exploitation through an active management approach. The proposed method establishes a contribution to adjusting the regulation systems in order to facilitate DNOs to invest in innovation.

D. *Paper Organization*

Section II provides an overview of the regulatory asset and innovation for DNOs. Section III describes the optimization method based on NSGA-II and MP-OPF that is described in Section IV. Section V presents some simulation results. A discussion on the presented results and conclusions are given in Section VI.

II. REGULATORY ASSET AND INNOVATION FOR DNOs

The main drivers for network investments in new technologies for SGs are RES and DG integration, energy market and demand side management issues [27], reliability and quality of supply improvements, increase in energy demand, storage integration, optimization of operational and investment costs, electro mobility integration, increase of energy efficiency [28]–[30]. Despite these drivers, however, some barriers are slowing the spread of SGs. The main barriers are due to the contrasting policy and little incentives, to financial disincentive for the utilities that should develop a new business model, to the uncertainty related to about who should bear the high capital investment costs and receive the benefits. The utilities are, thus, trying to find support from the government and calling on regulators to agree on clear rules for how the costs and benefits of investments in SGs will be shared among different actors [28]–[30].

There is, therefore, a growing consensus according to which the adoption of appropriate public policies and their effective implementation can be the main drivers for a successful modernization of electrical, telecommunications, water and gas infrastructures. The basis for these policies is the adoption of a suitable regulation that offers incentives to system operators to ensure that they operate efficiently, making the right investments. The regulatory regime for innovative markets in the telecommunications sector is discussed in [31]. The authors argue that the cost-based regulation hinder the development of infrastructure-based competition in the highly dynamic telecommunications industry.

In the electrical sector, regulators objective is the maximization of social welfare that, in addition to reduction of costs, also includes balancing between the interests of customers, distribution companies, asset owners and society. While asset owners necessitate a reasonable return on invested capital, distribution companies desire to guarantee a stable business environment and gather satisfactory profit in order to operate and develop the network. Conversely, customers essentially desire reasonable pricing of electricity and an adequate level of the quality of supply, while society is also concerned in developing the essential infrastructure network [20]–[22].

The types of regulations defined for the DNOs are mainly technical and economic regulations: the former establishes the technical rules for the operation and planning of the distribution system, also guaranteeing an acceptable level of the service quality. Economic regulation aims, instead, at safeguarding customers from monopoly exploitation and balancing the controversial requirements of different stakeholders of the electricity distribution business: customers, society, distribution companies and owners [32]. These controversial expectations give rise to challenges for the regulators that, in order to direct the expansion of the regulated industry according to identified strategic objectives, can also implement extensive incentive schemes. In some cases, even if regulators attempt to direct distribution companies to satisfy the interests of the public, they may involuntarily implement incentives that encourage companies to maximize their own profits, while carrying out non-optimal network design. This is mainly due to the asymmetry of the information between the company and the regulators that lack full information about the cost reduction potentials of the company. In many cases regulation design tends to be a continuous process and, in order to implement versatile incentive schemes, regulators need information on the cost attributes and other characteristics of the regulated industry. As a consequence, the continuous process, in some cases developed in a disorganized way, may generate a complex regulation model and a holistic analysis may be required in order to identify some directing signals.

A. Incentives for Innovation

Regulation is fundamental in order to assist the technical transformation of energy networks via incentives for participation in R&D and investments in new technologies [18]. In the energy industry, like in many other utilities, the most significant change in the regulatory regimes was the shift from rate of return to incentive regulation [33]–[37]. Innovation incentives, related to the reduction of grid expansion and operation costs and the increase of service quality levels are, thus, expected to play a major role in the future regulatory asset.

Mainly due to the below-average innovative character of the electricity network in the past [38], there are rarely studies of the relationship between regulation and innovation in the electricity grid. Thus, the issue of regulatory incentives for investments in electricity grid innovation is a quite new research area.

A full analysis of the most important results reached by the economic literature on incentive for the operators of the network industries is provided in [22]. Most of researches in this field compare the effects of cost-based regulation and incentive-based regulation on incentives to invest in network infrastructure. The effects of the rate-of-return regulation, the cost-plus regulation and cap-regulation on the speed and intensity of technological progress have been firstly examined in [39].

Some researchers conclude that the incentive regulation, in comparison to other regulation methods, provides significant incentives for short-term innovation and cost reduction, but the incentives for long-term infrastructure investment are limited [40], [41]. These investments and innovations are, indeed, mainly focused on a reduction of operational expenditures (OPEX). This cost reduction results in higher profits for the grid operator within the regulation period. Incentives for reducing capital expenditures (CAPEX) are, instead, more challenging to implement than for OPEX [41]. Studies focusing on the long-term effect of incentive regulation on innovations in the electricity sector are still rare in the literature. Moreover, there are no results assessing the impact of incentive regulation on product innovations CAPEX related to investments in SGs that remains a research objective. The main reason is that CAPEX are caused by investments with a long-term time horizon and significantly larger payback periods than the duration of the actual regulation period. The disincentive created by regulation on network innovations is discussed in [18], [41], and [42].

III. METHOD DESCRIPTION

A. Structure of the Method

The method, by allowing the evaluation of the economic impact of a considered incentive regulation that determines a consequent employment of AM schemes, is a useful tool for regulators, DNOs and developers. Regulators can determine how the incentives related to the investments in innovation in distribution networks effect the sharing of costs and benefits of investments in AM schemes among different stakeholders. In this way, the right incentive can be determined in order to favor the best integration and exploitation of wind energy. DNOs can compare various options related to new investments in innovation (i.e., the implementation of AM schemes) considering different issues, such as the innovation incentives, the installation of new WTs, planned by developers at particular buses, the effect of new AM schemes on its costs and benefits. DNO can also try to guide the allocation of new WTs installations in such a way to increase its revenues, mainly due to incentive regulation and energy losses reduction, while also favoring the integration and exploitation of wind energy. Developers can evaluate the profitability of their investment in new generation systems in active networks.

As DNO and WTs developers perceive different "optimal" locations and capacities for WTs, by comparing the two outcomes, and through the use of trade-off techniques, it may be possible to define a range of compromise solutions offering a potentially better arrangement for WTs under different incentive schemes.

With regards to the regulatory time horizons, recent U.K. regulation is considered according to which DNO receives an annual payment from the developers for every kW of connected wind capacity for 15 years [43], [44]. It includes both the incentive rate for efficient connection of DG to the network and the O&M allowance to cover the on-going O&M costs of the DG connection assets. DNO also receives an incentive scheme to reduce energy losses: the regulator sets a target losses level for each DNO and DNOs are rewarded if losses are below this and penalized if they are above. It is considered that DNO also receives an annual payment from an incentive mechanism to promote innovation for the first five years. Registered power zones (RPZ), a mechanism addressed by Ofgem, is, indeed, assumed. RPZ scheme is focused specifically on the connection of DG to distribution systems and encourages the development of new, cost effective, innovative technologies and connection solutions. Typical projects within the RPZs focus on active voltage control, fault level management and power flow control. It is worth noting that according to the assumed scheme [43], [44], the costs incurred by the DNOs to provide network access to DG are given a partial pass-through treatment. Even if the U.K. regulation is considered in order to carry out the presented analysis, the method can be adapted to different regulations.

The structure of the proposed hybrid optimization used to generate the Pareto front is shown in Fig. 1. NSGA II is used in order to select the type and number of WTs to be allocated at each candidate bus. It randomly generates the initial population of solutions (individuals) by defining a set of vectors. Each vector, or called a chromosome, has a size $N_e = N_C \times N_T$, where N_C is the number of candidate locations and N_T is the number of defined WT types.

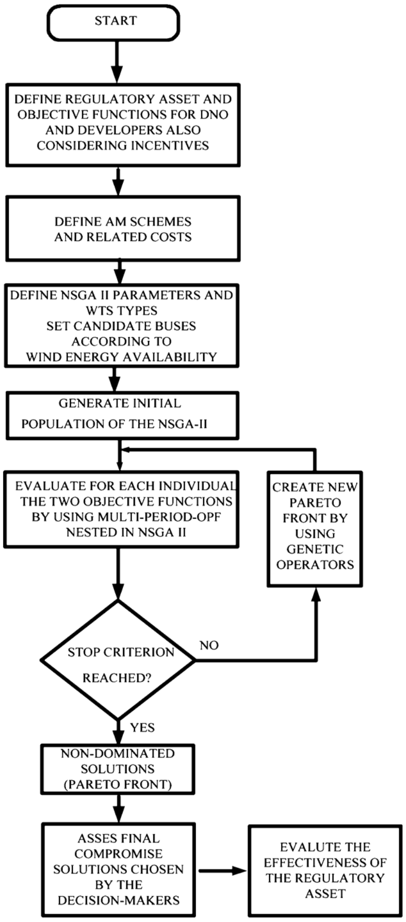

Fig. 1. Structure of the method.

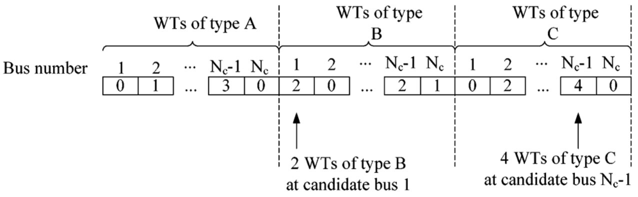

Fig. 2. NSGA chromosome.

As shown in Fig. 2, a chromosome consists of a vector of integers, each of which represents the number of WTs of a given type to be allocated at a candidate bus. For instance, WTs of type A is associated with the first part of the vector with the size of N_c, which is the number of the candidate locations. Each element of this vector is an integer representing the number of WTs of type A connected to the corresponding bus. As such, the locations and types of WTs are expressed as a string of integers. For each chromosome of NSGA, specifying the number and locations of WTs, the maximum wind energy generation or the minimum energy losses over a year are assessed by running a MP-OPF algorithm including AM schemes.

B. Objective Functions of NSGA

When considering WTs developers preferences, in order to analyze the profitability of the WTs investment, the NSGA objective function is the NPV, defined as the difference between the discounted cash flows and the investment cost:

$$NPV_{dev}(\mathbf{y}) = -IC^{WT}(\mathbf{y}) - IC^{AM}_{dev}(\mathbf{y}) + \sum_{n=1}^{N} \frac{FC_n^{dev}(\mathbf{y})}{(1+r)^n} \tag{1}$$

where $\mathbf{y}$ is the optimization variable of the NSGA, r is the interest rate, N is the planning horizon (i.e., 15 years), IC^{WT} is the initial investment cost related to the WTs installation, IC_{dev}^{AM} is the initial investment cost related to the AM implementation paid by developers. It is worth noting that there is no cost associated with network reinforcement as the analysis constrains WT capacity within the network limits. FC_n^{dev} is the total annual revenue obtained by developers selling energy at year n, defined as

$$FC_n^{dev}(\mathbf{y}) = \sum_{h=1}^{8760} E_n^h(\mathbf{y}) \times p_n^h(\mathbf{y}) \tag{2}$$

where E_n^h (MWh) is the wind energy dispatched by WTs at hour h and year n; p_n^h (£/MWh) is the developer's net revenue per MWh of sold energy at hour h and year n (set at 43.13 £/MWh).

When considering DNOs preferences, the objective function is the NPV defined as the difference between the discounted cash flows coming from the rewarded incentives and the investment cost related to the AM implementation paid by the DNO:

$$NPV_{DNO}(\mathbf{y}) = -IC_{DNO}^{AM}(\mathbf{y}) + \sum_{n=1}^{N} \frac{FC_n^{DNO}(\mathbf{y})}{(1+r)^n} \tag{3}$$

where FC_n^{DNO} is the total annual revenue obtained by the DNO at year n, defined, according to the recent U.K. regulation [20], [37]–[39], as

$$FC_n^{DNO}(\mathbf{y}) = C_L\left(L_n^t - L_n^a(\mathbf{y})\right) + P^{WT}\left(C_n(\mathbf{y}) + C_n^{RPZ}(\mathbf{y})\right)$$

where C_n is the annual payment that DNO receives from the developers for every kW of connected wind capacity (P^{WT}) for 15 years (2£/kW/year). It includes both the incentive rate for efficient connection of DG to the network and the O&M allowance to cover the on-going O&M costs of the DG connection assets. C_n^{RPZ} is the annual payment that DNO receives from the RPZ incentive mechanism to promote innovation for the first five years. For all designated RPZs the incentive element of the DG incentive is increased for the first five years of operation by 3£/kW. C_L represents the losses incentive that rewards or penalizes each DNO according to how they perform against a losses target. The incentive is set at 60 £/MWh. $L_n^a(\mathbf{y})$ and L_n^t are, respectively, the actual and target energy losses (MWh) during year n.

In addition to the load variation over each year, also a load growth of 1% every year has been assumed. Moreover, the capacity factor (CF) of WTs is evaluated according to the wind generation data and the WTs' capability curves. In order to take in account long term CF, it is assumed that the CF of WTs declines up to 1% per year during the planning horizon [4]. The reason could be either wind variations or reduced performance of WTs because of wear and tear.

C. NSGA-II

Different mathematical and evolutionary algorithms for finding non-dominated solutions of a multi-objective optimization problem exist [47], [48]. Even if most of them, based on a single-objective weighted-sum or another single-objective approach can also find multiple Pareto optimal solutions, some drawbacks exist. They are mainly due to their incapacity to generate different optimal solutions and to attain a uniformly distributed set of Pareto-optimal solutions with a uniform setting of weight vectors.

GA, in general, can effectively handle nonlinear, non-convex, and mixed integer optimization problems [49], [50] and with some modifications can be used to capture and preserve multiple Pareto-optimal solutions. The genetic-based NSGA II [49], [50] is used in the proposed method to solve the multi-objective optimization and generate non-dominated solutions. It demonstrated to be among the most efficient algorithms for multi-objective optimization on a number of benchmark problems. It offers the advantage that, due to simultaneous search of multiple solutions, multiple Pareto-optimal solutions can be found all together in one single simulation run. Moreover, NSGA II is computationally faster than other algorithms and ideal for finding a well-distributed set of Pareto-optimal solutions thanks to a parallel and an efficient search. In NSGA II a solution population is organized into a number of non-dominated fronts: all individuals not dominated by any other individuals are assigned front number one. Front number two is assigned, then, to all individuals only dominated by individuals in front number one, and so on. A fitness, based on its level of non-dominancy, is assigned to each solution. In order to preserve the diversity of solutions, assigned fitness are degraded based on the number of neighboring solutions and according to their Euclidian distances. At each iteration, new individuals are generated and the reproduction of population is attained through classical crossover and mutation process. NSGA-II algorithm and its detailed implementation procedure can be found in [49], [50].

IV. MULTI-PERIOD OPF WITH ACTIVE MANAGEMENT SCHEMES

A. Modeling of Time-Varying Load and Wind Power Generation

The MP-OPF, including AM schemes has been already presented in [7]. It includes the time-varying characteristics of the load demand and wind power generation. For the modeling of time-varying load and wind power generation, real data from a local distribution network have been used and processed. Based on their joint probability of occurrence, defining the number of coincident hours over the year, wind availability and demand have been aggregated into a number of wind/demand scenarios [7], [13]. The set of scenarios obtained by combining wind availability and load demand real data for one year have been considered. Each scenario represents the combination between wind speed and load demand values, indicated in percentage terms, and is characterized by a defined number of hours over the year. Such a number represents the time (number of hours) during which each combination wind/demand occurs in the course of the year [13]. Each type of day consists of 24 hours, each of which can have 400 $(10 \times 10 \times 4)$ different combinations of load-generation, as two different wind speed distributions at buses have been assumed. In order to create the multi-period interdependency, at each iteration of the MP-OPF there are a unique set of WTs capacity variables with 400 sets of power flow variables.

B. Active Management Schemes

In the proposed method, the area-based control strategy of on-load tap changers (OLTCs), based on measurements from various locations of the network, is used. In this way, the voltage regulation of OLTCs can be based on the voltage information of the bus that has the most severe over voltage problem. Energy curtailment is implemented at each period by introducing a negative generation variable to represent the curtailed energy from each WT. For a given period, the maximum energy that can be curtailed from a given WT is set to a fraction of the potential energy that the WT could have produced without energy curtailment. Power factors of WTs can be controlled so that wind energy penetration level in the network is maximized or power losses are minimized [13].

C. Objective Functions of the MP-OPF

When considering the WTs developers preferences, the MP-OPF objective function to maximize is

$$E = \sum_{j=1}^{N_j} \sum_{g=1}^{N_G} E_g^j(P_g, \mathbf{x_j}) \tag{4}$$

where $E_g^j(P_g, x_j)$ is the wind energy generated during the time period j by the gth WT with rated capacity P_g, N_j is the total number of periods in a year corresponding to different combinations of load demand and wind power generation; N_G is the number of WTs (indexed by g). The vector x_j consists of a set of controllable quantities and dependent variables during each period j. The optimization variables include for each period j: the secondary voltage of the OLTC, the power factor angle and the curtailed energy of each WT, and the import/export power at the interconnection to the external network.

When considering the DNOs preferences the MP-OPF objective function to minimize is

$$P_{Losses} = \sum_{j=1}^{N_j} P_{losses}^j(\mathbf{x_j}) \tag{5}$$

where P_{losses}^j are the active energy losses during period j.

Both objectives are subject to a number of technical constraints: $\mathbf{h}(x_j) = 0, \mathbf{g}(x_j) \leq 0$, imposed by regulations including bus voltage limits, line/transformer thermal limits, and system short-circuit levels [13]. By fulfilling these constraints, the network reinforcement due to the connection of WTs may be avoided. The equality constraints $\mathbf{h}(x_j)$ represent the static load flow equations such as Kirchhoff current law and Kirchhoff voltage law. The inequality constraints $\mathbf{g}(x_j)$ are listed in the following.

- — Capacity constraints for the interconnection to external network (slack bus),
- — Capacity constraints for the WTs: maximum capacity that may be installed at each,
- — Voltage level at buses,
- — Flow constraints for lines and transformers,
- — Short-circuit level constraint.

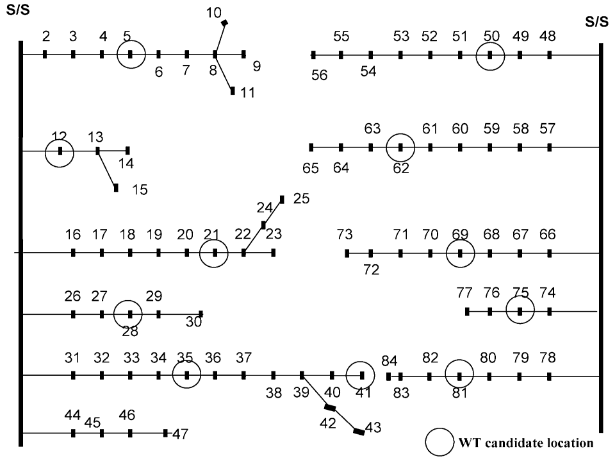

Fig. 3. 84-bus network indicating potential locations for WTs.

The additional constraints derived from the active management schemes are:

- — Curtailed energy constraint,
- — Coordinated on-load tap-changer voltage constraint,
- — Coordinated generator reactive power constraints.

V. CASE STUDY

An 84-bus 11.4-kV radial distribution system [7] is used to demonstrate the effectiveness of the proposed approach. The network is a three phase balanced network. The eleven feeders are supplied by two 20-MVA, 33/11.4-kV transformers as shown in Fig. 3. Eleven candidate buses have been assumed, as shown in Fig. 3, in particular buses 5, 12, 21, 28, and 35 are characterized by a mean wind speed of about 6 m/s, while buses 41, 50, 62, 69, 75, and 81 are characterized by a mean wind speed of about 10 m/s.

A. Network Constraints

Voltage limits are taken to be ±6% of nominal and feeder thermal limits are 5.1 MVA (270 A/phase). Load demand variations during the first and last year of the planning horizon are shown in Table I. The substation power exports to the upstream grid are limited to the capacity of the transformers (40 MVA). Power factor is assumed to vary between 0.9 leading and 0.9 lagging when the coordinated generators reactive power control option is considered. The short-circuit limit constraint of 200 MVA has been assumed accordingly to the designed short-circuit capacity for the network and the short-circuit calculations method described in [13] are used.

B. Investment Costs

It is assumed that WTs of three different capacities are chosen by the WT developers. The sizes of the WTs have been selected according to the load demand for the considered distribution system. These capacities are 225 kW, 660 kW, and 900 kW.

Table II lists the capital costs (C_c) associated to the three candidate WTs. Maximum four WTs can be allocated at a given

TABLE I
LOAD DEMAND DURING THE FIRST AND LAST YEAR OF THE PLANNING HORIZON

Year	**Active Power [MW]**		**Reactive Power [MVAR]**	
	Min	Max	Min	Max
1	6.53	13.05	5.30	10.61
15	7.50	15.00	6.10	12.20

TABLE II
CAPITAL COSTS (C_c) ASSOCIATED TO THE THREE CANDIDATE WTs

WT Type	**Rated output electric power [kW]**	**Capital cost [£/kW]**	**Total capital cost [k£]**
A	225	1207.50	27.17
B	660	1035.00	68.31
C	900	7763.30	69.86

location. This requirement may be set by the available land for building WTs.

The considered AM schemes are:

1) Coordinated area-based control with OLTCs for the control and measurement system at the substation and for the voltage measurement system at each feeder
2) Reactive power control for a single WT (power factor control)
3) Active power control for a single WT (generation curtailment)

The devices required for the implementation of coordinated area-based control are:

- two OLTC relays,
- an automatic voltage control (AVC) relay receiving instructions from the supervisory control and data acquisition (SCADA) in order to control the OLTC relays,
- a voltage transformer connected at the lower voltage side of the substation, suitable for measurement and control purposes,
- a voltage transformer, a transducer and a remote telemetry units (RTU) installed at each feeder in order to measure the voltage at every feeder connected to the substation,
- a SCADA and RTUs.

The devices required for the implementation of reactive power control and generation curtailment for a single WT are:

- a voltage transformer and a transducer for measurement and control purposes,
- a SCADA system which processes the voltage measurements and the instructions it receives from the network operator and controls the operation of the compensator,
- an RTU used as interface between the control and measurement system at the reactive compensator and the communication system with the DNO.

The use of power line communication is assumed, so no additional cost for the communication is incurred by the network operator. In order to evaluate the cost incurred for the implementation of AM schemes, data derived as a result of a survey that was carried with three DNOs in the U.K. [16] are considered. The cost of coordinated area-based control with OLTCs is estimated at 12.94 k£ while the cost of reactive power control and generation curtailment options is estimated at 3.45 k£. Even if different sharing of costs can be determined by the regulator, in the presented case study, it is assumed that the DNO bears the cost for coordinated area-based control, while the costs of reactive power control and generation curtailment are paid by WT developers [16].

C. NSGA Parameters

The time-resolution of the MP-OPF assessment is one year, so for every chromosome of the NSGA, the MP-OPF should be carried out 15 times.

The basic parameters of the NSGA-II are summarized as follows. The total control variables are $33(= 3 \times 11)$, corresponding to the number of three types of WTs at the eleven candidate locations. The population size of each generation is 30. The initial population is generated at random between zero and three.

The GA stops if any of the following conditions is reached:

1) the maximum generation number exceeds 300,
2) there is no improvement in the Pareto front for 50 consecutive generations.

Sensitivity analyses have been carried out to consider different values for the NSGA-II parameters such as stop criteria, population size and genetic operators. From these analyses, it was shown that the used values guarantee the convergence of the algorithm to a satisfactory solution.

D. Simulation Results

The proposed method is applied to the abovementioned distribution network. The method has been implemented in MATLAB incorporating some features of MATPOWER suite [51], [52] and MATLAB toolbox for NSGA-II [49], [50].

Different simulations have been carried out in order to assess the influence of AM schemes and RPZ incentives on the set of available solutions that can be selected by the stakeholders.

As known, renewable energy targets can be stated as a percentage of overall capacity allocations or as a single target. In both cases, these commitments should be clearly delineated and well-defined in plans and strategies including precise timeframes. On these bases and, in order to illustrate the results of some selected non-dominated solutions, some scenarios have been assumed in which the regulator targets a cumulative installed wind capacity also according to the load demand.

Case A: Fig. 4 shows the Pareto fronts obtained in the cases without and with AM schemes and RPZ incentive. The objective function related to WTs developers varies between around 6.91 and 12.84 M£ in the case without AM schemes, while the implementation of AM schemes and RPZ incentive allows an increase of wind energy generation, with an NPV varying between around 7.99 and 14.58 M£. The best solution for developers is characterized by an NPV of around 14.58 M£, an installed wind capacity of about 23.48 MW with an installation cost for WTs of about 21 M£. The higher NPV is mainly due to the combined operation of AM schemes that consent to alleviate voltage constraints.

When looking at the objective function related to the DNO, it is worth noting that, depending on the energy losses and on the installed wind capacity, the application of AM schemes and RPZ incentive translates into an higher incentive. Without AM

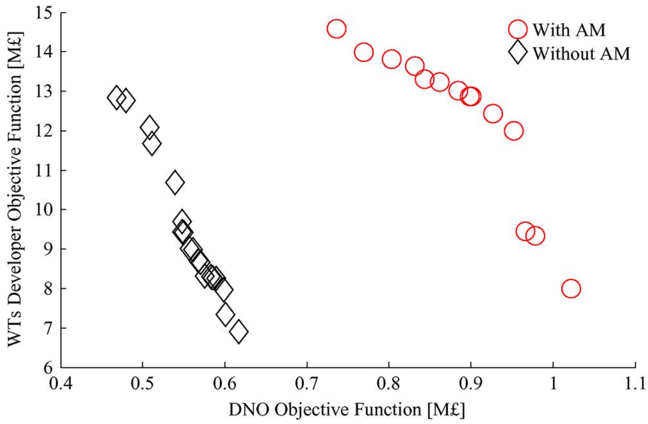

Fig. 4. Final population of NSGA-II (Case A).

TABLE III
RESULTS FOR CASE B WITHOUT AM SCHEMES

Solution	Developer Objective Function [M£]	DNO Objective Function [M£]
1	12.77	0.48
2	12.84	0.47
3	12.09	0.51

TABLE IV
RESULTS FOR CASE B WITH AM SCHEMES

Solution	Developer Objective Function [M£]	DNO Objective Function [M£]
1	12.00	0.95
2	13.24	0.86
3	12.87	0.90
4	12.44	0.93
5	12.87	0.90
6	13.01	0.88
7	13.81	0.80

schemes the DNO objective function varies between around 0.47 and 0.62 M£, while the adopted AM schemes determine an increase with a value varying between around 0.74 and 1.02 M£. It can be evidenced that the non-dominated solutions in the case of AM schemes and RPZ incentive generally allow DNO improving its profits if compared to the solutions obtained without AM schemes. The combined operation of AM schemes, while alleviating voltage constraints, allows reducing power losses with a consequent increase of the incentives received by the DNO.

Case B: Further analysis of the results can be obtained by making some assumptions on the regulatory constraints related to the required capacity of RES and on the NPV desired by all the involved stakeholders. By assuming that DNO is obliged to accept a minimum installed wind capacity of 25 MW in order to satisfy mandatory targets set by the directive on the promotion of the use of energy from RES and that WTs developers aim at obtaining a minimum NPV of 12 M£, the available solutions are shown in Tables III and IV and in Fig. 5.

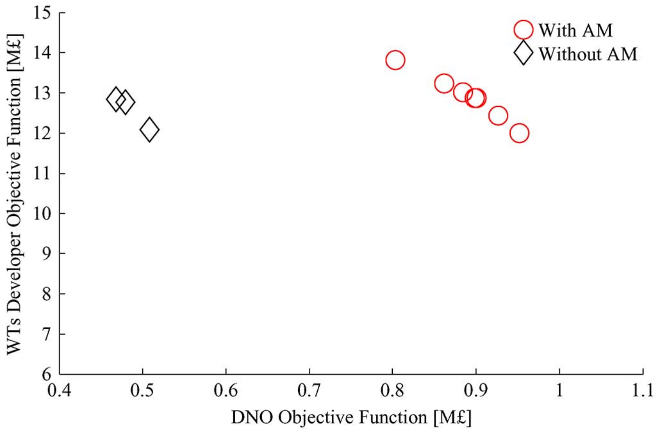

Fig. 5. Final population of NSGA-II with constraints (Case B).

TABLE V
INSTALLED CAPACITY AT BUSES IN CASE B WITH AM SCHEMES CONSIDERING THE BEST SOLUTION FOR DNO

Bus	Capacity [kW]
5	2445
12	2250
21	2010
28	2220
35	2010
41	1770
50	3360
62	2925
69	2685
75	2685
81	3120

In this case, the best solution for DNO is characterized by an NPV of around 0.95 M£, while it is worth noting that without AM schemes the same solution would reduce the NPV of DNO to only 0.51 M£. The WTs developer objective function of around 12 M£ corresponds to an installed capacity of 27.48 MW with an installation cost for WTs of about 24.72 M£. The installed capacities at candidate buses, as shown in Table V, vary between 1.77 MW at bus 41 and 3.36 MW at bus 50 and is generally equally allocated among candidate buses characterized by the same mean wind speed. In particular higher capacities are sited at buses with a mean wind speed of 10 m/s (i.e., at bus 81 four WTs are installed of which two of 660 kW and two of 900 kW).

Case C: In this case, the same assumptions of case B are considered, but with an increase of 50% of the cost of AM schemes implementation. The set of available solutions are shown in Table VI in the case that the expenses for AM schemes are shared between WTs developers and DNO as in the previous cases.

The set of available solutions when considering that all the costs of AM schemes are paid by the DNO are shown in Table VII. It is worth noting that also in this case, the DNO is advantaged by AM schemes implementation with an objective function varying between around 0.74 and 0.89 M£.

VI. CONCLUSIONS AND DISCUSSION

The integration of decentralized RES requires the assessment of investments in innovation and smart solutions that are greatly

TABLE VI
RESULTS FOR CASE C WITH AM COSTS SHARED BETWEEN DNO AND WTS DEVELOPERS

Solution	Developer Objective Function [M£]	DNO Objective Function [M£]
1	13.22	0.86
2	12.85	0.89
3	12.42	0.92
4	12.85	0.89
5	12.99	0.88
6	13.79	0.80

TABLE VII
RESULTS FOR CASE C WITH AM COSTS PAID BY DNO

Solution	Developer Objective Function [M£]	DNO Objective Function [M£]
1	12.04	0.89
2	13.27	0.80
3	12.90	0.84
4	12.48	0.86
5	12.90	0.84
6	13.04	0.82
7	13.85	0.74

influenced by the regulatory environment. An important requisite to take into account in the regulatory asset for DNOs is that of carrying out innovative SGs implementations. Regulators should, therefore, decide what investment incentives are desirable and design a flexible economic regulatory framework that allows DNOs deciding the right investments. Accordingly, the effects of AM schemes and innovation incentive regulation on the decision of stakeholders concerned with WTs investments have been assessed in this paper. In contrast to the present literature, that is mainly theoretical, an innovative, repeatable method that can be applied to different electricity regulation systems has been proposed. The method, considering investments in innovation in a distribution network, allows the involved stakeholders (regulators, DNOs, developers) evaluating the benefits of AM schemes related to the integration of RES. It also establishes a contribution to amending regulation systems to both current and future requirements with the aim of avoiding that standard incentive regulation design causes disincentives for investments in smart solutions. The method can, thus, support regulators in evaluating the possible benefits of AM investments and determining the right innovation incentives based on the assessment of the costs and benefits related to different investments and to whom they apply [31].

REFERENCES

[1] L. Baringo and A. J. Conejo, "Transmission and wind power investment," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 885–893, May 2012.

[2] L. Baringo and A. J. Conejo, "Wind power investment within a market environment," *Appl. Energy*, vol. 88, no. 9, pp. 3239–3247, Sep. 2011.

[3] P. Siano and G. Mokryani, "Probabilistic assessment of the impact of wind energy integration into distribution networks," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4209–4217, Nov. 2013.

[4] P. Siano and G. Mokryani, "Assessing wind turbines placement in a distribution market environment by using particle swarm optimization," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 3852–3864, Nov. 2013.

[5] G. Mokryani and P. Siano, "Combined Monte Carlo simulation and OPF for wind turbines integration into distribution networks," *Electr. Power Syst. Res.*, vol. 103, pp. 37–48, 2013.

[6] G. Mokryani and P. Siano, "Evaluating the integration of wind power into distribution networks by using Monte Carlo simulation," *Int. J. Electr. Power Energy Syst.*, vol. 53, no. 1, pp. 244–255, 2013.

[7] A. Piccolo and P. Siano, "Evaluating the impact of network investment deferral on distributed generation expansion," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1559–1567, Aug. 2009.

[8] P. Siano, L. F. Ochoa, G. P. Harrison, and A. Piccolo, "Assessing the strategic benefits of distributed generation ownership for DNOs," *IET Gener. Transm. Distrib.*, vol. 3, pp. 225–236, 2009.

[9] S. J. Kazempour, A. J. Conejo, and C. Ruiz, "Strategic generation investment using a complementarity approach," *IEEE Trans. Power Syst.*, vol. 26, no. 2, pp. 940–948, May 2011.

[10] C. Clastres, "Smart grids: Another step towards competition, energy security and climate change objectives," *Energy Policy*, vol. 39, no. 9, pp. 5399–5408, 2011.

[11] P. Chen, P. Siano, B. Bak-Jensen, and Z. Chen, "Stochastic optimization of wind turbine power factor using stochastic model of wind power," *IEEE Trans. Sustain. Energy*, vol. 1, no. 1, pp. 19–29, Apr. 2010.

[12] A. J. Conejo, J. M. Morales, and L. Baringo, "Real-time demand response model," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 236–242, 2010.

[13] P. Siano, P. Chen, Z. Chen, and A. Piccolo, "Evaluating maximum wind energy exploitation in active distribution networks," *IET Gener. Transm. Distrib.*, vol. 4, no. 5, pp. 598–608, May 2010.

[14] C. Cecati, C. Citro, A. Piccolo, and P. Siano, "Smart operation of wind turbines and diesel generators according to economic criteria," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4514–4525, Oct. 2011.

[15] P. Siano, C. Cecati, H. Yu, and J. Kolbusz, "Real time operation of smart grids via FCN networks and optimal power flow," *IEEE Trans. Ind. Informat.*, vol. 8, no. 4, pp. 944–952, Nov. 2012.

[16] S. N. Liew, "Technical and economic assessments of active distribution networks," Ph.D. dissertation, University of Manchester, Manchester, U.K., June 2002.

[17] Ofgem, Handbook for Implementing the RIIO Model, 2010.

[18] M. G. Pollit, "The future of electricity (and gas) regulation in a low-carbon policy world," *Energy J.*, vol. 29, pp. 63–94, 2008.

[19] R. Cossent, T. Gómez, and P. Frías, "Towards a future with large penetration of distributed generation: Is the current regulation of electricity distribution ready? Regulatory recommendations under a European perspective," *Energy Policy*, vol. 37, no. 3, pp. 1145–1155, 2009.

[20] C. Burns and C. Riechmann, "Regulatory instruments and investment behaviour," *Utilities Policy*, vol. 12, no. 4, pp. 211–219, 2004.

[21] P. J. Agrell and P. Bogetoft, "Network regulation under climate change policy review," European University Institute Working Papers RSCAS 67/2010, 2010.

[22] G. Guthrie, "Regulating infrastructure: The impact on risk and investment," *J. Econ. Lit.*, vol. 44, no. 4, pp. 925–972, 2006.

[23] T. Jamasb and M. Pollit, "Benchmarking and regulation of electricity transmission and distribution utilities: Lessons from international experience," *Utilities Policy*, vol. 9, no. 3, pp. 107–130, 2000.

[24] T. Jamasb and M. Pollit, "Incentive regulation of electricity distribution networks: Lessons of experience from Britain," *Energy Policy*, vol. 35, no. 12, pp. 6163–6187, 2007.

[25] S. Benedettini and F. Pontoni, "Electricity distribution investments: No country for old rules? A critical overview of UK and Italian regulations," Working Paper no. 50, 2012.

[26] K. Noyens, "The smartness barometer—How to quantify smart grid projects and interpret results," A Eurelectric Paper, 2012.

[27] P. Siano, "Demand response and smart grids—A survey," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 461–478, 2014.

[28] European Commission and European Technology Platform Smart Grids, Vision and Strategy for Europe's Electricity Networks of the Future. Brussels, Belgium, 2006.

[29] European Regulators Group for Electricity & Gas (ERGEG), Position Paper on Smart Grids—An ERGEG Conclusions Paper, Ref: E10-EQS-38-05, 2010.

[30] Union of the Electricity Industry (EURELECTRIC), Smart Grids and Networks of the Future—EURELECTRIC Views, Ref: 2009-030-0440, 2009.

[31] W. Magat, "Regulation and the rate and direction of induced technical change," *Bell J. Econ.*, vol. 7, no. 2, pp. 478–496, 1976.

[32] S. Honkapuro, "Business impacts and incentives of regulation for DSOs and Smart Grids," in *Proc. CIRED Prague*, 2009.

[33] P. L. Joskow, “Incentive regulation and its application to electricity networks,” *Rev. Netw. Econ.*, vol. 7, no. 4, pp. 547–560, 2008.

[34] M. A. Crew and P. R. Kleindorfer, “Regulatory economics: Twenty years of progress?,” *J. Regulat. Econ.*, vol. 21, no. 1, pp. 5–22, 2002.

[35] I. Vogelsang, “Electricity transmission pricing and performance-based regulation,” *Energy J.*, vol. 27, pp. 97–126, 2006.

[36] C. Cambini and L. Rondi, “Incentive regulation and investment: Evidence from European energy utilities,” *J. Regulat. Econ.*, vol. 38, no. 1, pp. 1–26, 2010.

[37] S. Nykamp, M. Andor, and J. L. Hurink, “‘Standard’ incentive regulation hinders the integration of renewable energy generation,” *Energy Policy*, vol. 47, pp. 222–237, 2012.

[38] European Technology Platform Smart Grids, Strategic Deployment Document for Europe’s Electricity Networks of the Future, 2010.

[39] P. Baake, U. Kameke, and C. Wey, “A regulatory framework for new and emerging markets,” *Commun. Strategies*, vol. 60, pp. 123–146, 2005.

[40] C. Müller, “New regulatory approaches towards investments: A revision of international experiences,” WIK Discussion Paper Number 353, 2011.

[41] L. Meeus and M. Saguan, “Innovating grid regulation to regulate grid innovation: From the Orkney Isles to Kriegers Flak via Italy,” *Renew. Energy*, vol. 36, pp. 1761–1765, 2011.

[42] D. Bauknecht, “Incentive regulation and network innovations,” EUI Working Paper, RSCAS, 2011.

[43] Ofgem, Electricity Distribution Price Control Review—Final Proposals, 2004.

[44] Ofgem, Electricity Distribution Price Control Review—Regulatory Impact Assessment for Registered Power Zones and the Innovation Funding Incentives, 2004.

[45] Ofgem, “Delivering desired outcomes: Ensuring the future regulatory framework is adaptable,” Regulating Energy Networks for the Future: RPI-X@20- Working Paper, 2009.

[46] R. A. Gallego, A. Monticeilli, and R. Romero, “Comparative studies on non-convex optimization methods for transmission network expansion planning,” *IEEE Trans. Power Syst.*, vol. 13, no. 3, pp. 822–828, Aug. 1998.

[47] A. Alarcon-Rodriguez, E. Haesen, G. Ault, J. Driesen, and R. Belmans, “Multi-objective planning framework for stochastic and controllable distributed energy resources,” *IET Renew. Power Gener.*, vol. 3, no. 2, pp. 227–238, Jun. 2009.

[48] A. Alarcon-Rodriguez, G. Ault, and S. Galloway, “Multi-objective planning of distributed energy resources: A review of the state-of-the-art,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 5, pp. 1353–1366, 2010.

[49] K. Deb, A. Pratap, A. Agarwal, and T. Meyarivan, “A fast and elitist multi-objective genetic algorithm: NSGA II,” *IEEE Trans. Evol. Comput.*, vol. 6, no. 2, pp. 182–197, Apr. 2002.

[50] P. K. Shukla and K. Deb, “On finding multiple Pareto-optimal solutions using classical and evolutionary generating methods,” *Eur. J. Oper. Res.*, vol. 181, pp. 1630–1652, Sep. 2007.

[51] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, “MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education,” *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 12–19, Feb. 2011.

[52] H. Wang, C. E. Murillo-Sánchez, R. D. Zimmerman, and R. J. Thomas, “On computational issues of market-based optimal power flow,” *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1185–1193, Aug. 2007.

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