Stochastic System of Systems Architecture for Adaptive Expansion of Smart Distribution Grids

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***Abstract*—The incorporation of the reconfiguration into the expansion planning of smart distribution networks is addressed in this paper, in which the potential of distributed energy resources (DERs) and demand response (DR) are modeled. The system of systems (SoS) architecture is employed to model the strategy of a distribution company (DISCO), a private investor (PI) and a DR provider (DRP). The SoS is an efficient modeling architecture to model the behavior of independent and autonomous systems with distinct objective functions who are able to share some data and work together. The aim of the DISCO is to upgrade the system with the optimal cost and reliability, while the PI and DRP want to maximize their profit. The DISCO should try to persuade the PI to install DGs (Distributed generations) by offering the guaranteed purchasing prices. Furthermore, the DRP is a market player who can negotiate with the DISCO to sign a contract to sell the purchased DR capacities from the customers. The uncertainties of the DISCO problem is handled by using the chance-constraint (CC) method, but the PI and DRP use the conditional value at risk (CVaR) method to model their uncertainties. Finally, to solve the proposed model, the multiobjective optimization algorithm is employed.**

***Index Terms*— Distribution expansion planning, Chance-constraint, Conditional value at risk, Demand response provider, Private investor, System of systems architecture.**

I. NOMENCLATURES

Abbreviations

DER	Distributed energy resource;
DR	Demand response;
DISCO	Distribution company;
PI	Private investor;
DRP	DR provider;
SoS	System of systems;
CC	Chance-constraint;
CVaR	Conditional value at risk;
DEP	Distribution expansion planning;
EENS	Expected energy not-supplied;
MOPSO	Multi-objective particle swarm optimization;
DSR	Distribution system reconfiguration;
O&M	Operation and maintenance;
VaR	Value at risk;

Indicators

y	Planning years;
n_{cl}	Network candidate lines;
T	Time periods;
n_f	Network feeders;
b^P	Candidate buses to install DERs by the PI;
j^P	Different types of DERs belonging to the PI;
b^R	Candidate buses that contain responsive customers to DR;
m	Bus numbers;
s^P	Scenarios that are considered by the PI;
s^{DR}	Scenarios that are considered by the DRP;

Decision variables

$\chi_{n_{cl}}(y)$	Integer variable that is "*CT*" if feeder "n_{cl}" is Reinforced with line type "*CT*"; otherwise, it is 0;
$z_{n_{cl}}(y)$	Binary variable that is 1 if feeder "n_{cl}" is reinforced in year "*y*"; otherwise it is 0;
$z_{n_f}(T,y)$	Binary variable that is 1 if feeder "n_f" is selected in time period "*T*" of year "*y*"; otherwise it is 0;
$x^P_{j^P,b^P}(y,s^P)$	New installed capacity of "j^P th" DER at bus "b^P" in year "*y*" in scenario "s^P" [kW];
$\pi^P_{b^P}(y)$	Guaranteed price to purchase the generation of DERs at bus "b^P" in year "*y*" [$/kWh];
$\pi^{DR}_{b^R}(y)$	The purchasing price of DR at bus "b^R" by the DISCO from the DRP in year "*y*" [$/kWh];
$p^{DR}_{b^R}(y,s^{DR})$	Active power of DR at bus "b^R" in year "*y*" and scenario "s^{DR}" [kW];
$\partial_{n_f}(y)$	Integer variable that is "*CT*" if the type of feeder "n_f" is "*CT*"; otherwise it is 0;

Variables

$C^{upg}(y)$	Network upgrading cost in year "*y*" [$];
$C^{Loss}(y)$	Total cost of energy losses in year "*y*" [$];
$C^{tr}(y)$	Total cost of imported energy from the transmission grid [$];
$C^{SoS}_{DG}(y)$	Total cost to persuade the PI to invest in year "*y*" [$];
$C^{DR}(y)$	Total cost to have contract with DRP in year "*y*" [$];
$p^{loss}_{n_f}(T,y)$	Active power losses of feeder "n_f" in the time period "*T*" of year "*y*" [kW];
$p^{tr}(T,y)$	Imported power from the transmission grid in time period "*T*" of year "*y*" [kW];
$p^P_{j^P,b^P}(y,s^P)$	Active power generation of the new installed DER with the type of "j^P" at bus "b^P" in year "*y*" in scenario "s^P" by the PI [kW];
$p^{QP}_{j^P,b^P}(y)$	Guaranteed active power generation of "j^P th" DER by PI at bus "b^P" in year "*y*" [kW];
$p^{QP}_{b^P}(y)$	Guaranteed active power generation by the PI at bus "b^P" in year "*y*" [kW];
$q^{QP}_{b^P}(y)$	Guaranteed reactive power generation by the PI at bus "b^P" in year "*y*" [kVAr];
$pf_{n_f}(T,y)$	Power flow of feeder "n_f" in the time period "*T*" of year "*y*" [kW];
$f^P(y,s^P)$	Benefit function of the PI in year "*y*" and scenario "s^P" [$];
ξ^P	The VaR in the stochastic optimization problem of

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	the PI [\$];
$\eta^{P}(y,s^{P})$	Auxiliary and positive variable to calculate the CVaR in year “y”;
$f^{DP}\left(y,s^{DR}\right)$	Benefit function of the DRP in year “y” and scenario “ s^{DR} ” [\$];
ξ^{DR}	The VaR in the stochastic optimization problem of the DRP [\$];
$\eta^{DR}(y,s^{DR})$	Auxiliary and positive variable to calculate the CVaR in year “y”;
$p_{b^R}^{QDR}\left(y\right)$	Guaranteed active power potential of DR by DRP at bus “ b^{R} ” of year “y” [kW];
$q_{b^R}^{QDR}\left(y\right)$	Guaranteed reactive power potential of DR by DRP at bus “ b^{R} ” of year “y” [kVAr];
$V_{m}\left(T,y\right)$	Voltage level of bus “m” in the time period “T” of year “y” [kV];
$I_{n_f}\left(T,y\right)$	Current of feeder “ n_f ”in the time period “T” of year “y” [A];
$P_{sub}\left(T,y\right)$	Injected active power from the distribution substation in the time period “T” of year “y” [kW];
$Q_{sub}\left(T,y\right)$	Injected reactive power from the distribution substation in the time period “T” of year “y” [kVAr];
$q_{n_f}^{loss}\left(T,y\right)$	Reactive power losses of feeder “n_f” in the time period “T” of year “y” [kVAr];
$pc\left(y\right)$	Total planning cost in year “y” [\$];
$e_{j^P,b^P}\left(y,s^{P}\right)$	Produced pollution of “ j^{P} ,th” DER at bus “ b^{P} ,th” in year “y” and scenario “ s^{P} ” [ton];

Parameters

$UC\left(\chi_{n_{cl}}\left(y\right)\right)$	Installation cost of line “CT” per kilometer [\$/km];
$L^{n_{cl}}$	Length of line “n_{cl}” [km];
$C_{n_{cl}}^{f}$	Fixed cost of feeder “n_{cl}” [\$];
$t\left(T,y\right)$	Duration of time period “T” in year “y” [h];
$LC\left(T,y\right)$	Loss cost in time period “T” of year “y” [\$/kWh];
$EC\left(T,y\right)$	Cost of imported energy from the transmission grid in time period “T” of year “y” [\$/kWh];
Y	Total planning years [year];
i	Discount rate;
$\lambda\left(\partial_{n_f}\left(y\right)\right)$	Failure rate of line “CT” per kilometer and per year [fail/(kmyear)];
$rp\left(\partial_{n_f}\left(y\right)\right)$	Average duration of fault on line “CT” [h/fail];
L^{n_f}	Length of line “n_f” [km];
$\alpha_{j^P,b^P}\left(y\right)$	Correction factor regarding the total power generation hours with the “ $j^{P\ th}$” DER at bus “ b^{P} ” in year “y”;
$C_{j^P}^{O\&M}\left(y\right)$	O&M cost of “ $j^{P\ th}$” DER in year “y” [S/kWh];
$I_{j^P}^{P}$	Investment cost of “ $j^{P\ th}$” DER for the PI [\$/kW];
Γ_{j^P}	Life-time of the “ j^{P} ,th” DER;
$\sigma^{P}(s^{P})$	Probability of scenario “ s^{P} ” that is considered by the PI;
θ^{P}	Risk factor of the PI;
τ^{P}	Confidence level of the PI;
$\sigma^{DR}(s^{DR})$	Probability of scenario “ s^{DR} ” that is considered by the DRP;
θ^{DR}	Risk factor of the DRP;
τ^{DR}	Confidence level of the DRP;
V^{min}	Minimum allowable voltage threshold [kV];
V^{max}	Maximum allowable voltage threshold [kV];
$I_{n_f}^{\max}\left(y\right)$	Maximum current limit of feeder “ n_f ” in year “y” [A];
$p_{m}\left(T,y\right)$	Active load at bus “m” in the time period “T” of year “y” [kW];
$q_{m}\left(T,y\right)$	Reactive load at bus “m” in the time period “T” of year “y” [kVAr];
$pc^{max}\left(y\right)$	Maximum value of financial resources for the DISCO in year “y” [\$];
$p_{j^P,b^P}^{DG,max}\left(y\right)$	Maximum capacity of “ j^{P} ,th” DER at bus “ b^{P} ”in year “y” [kW];
$p_{b^P}^{DG,max}\left(y\right)$	Maximum generation of DERs’ at bus “ b^{P} ” in year “y” [kW];
$p^{DG,max}\left(y\right)$	Maximum generation of DERs in network in year “y” [kW];
$x^{max}\left(y\right)$	Maximum of DER installation with the PI in year “y” [kW];
$e^{max}\left(y\right)$	Maximum permissible value of pollution emission in year “y” [ton];
$p_{b^R}^{DR,max}\left(y\right)$	Maximum capacity of DR at bus “ b^{R} ” in year “y” [kW];

Sets

Λ^{cl}	Set of all candidate lines;
Ψ	Set of planning years;
Λ^{f}	Set of all network feeders;
Υ	Set of time periods;
B^{P}	Set of candidate buses to invest DERs by the PI;
Ξ^{P}	Set of DER types belonging to the PI;
B^{R}	Set of candidate buses with responsive customers to DR;
Δ	Set of system buses;
Ω^{P}	Set of scenarios that is considered by the PI;
Ω^{DR}	Set of scenarios that is considered by the DRP.

II. INTRODUCTION

DEP is to determine the location, size and time of installing new instruments or upgrading the existing facilities, in order to satisfy the consumers’ demand [1]. The planners should upgrade the system to meet the increasing load level in a cost-effective and reliable manner. The expansion options of distribution systems (feeders, substations, DERs, etc.), the modeling methods (such as stochastic models), the optimization algorithms (like mathematical and heuristic), multi-stage and multi-objective problems are investigated with numerous studies [2]-[4]. Since DEP is a multi-objective and combinatorial optimization problem, heuristic optimization algorithms such as MOPSO, non-dominated sorting genetic algorithm and shuffled frog leaping method are interested, while they cannot guarantee the best solution [5], [6]. MOPSO is one of the best methods to solve the multi-objective problem, due to its capability in controlling parameters and its flexible applications [7]. The results of the multi-objective problems are the set of solutions called Pareto-curve, where each solution has some advantages compared to other solutions. Many methods have been proposed to select the best solution among the Pareto solutions, including fuzzy set, analytical hierarchy process, knee set, max–min, etc. [8]. However, the decision makers have their own policies and priorities, as well as their limitations regarding different objective functions, such as economic limits, or reliability constraints. Hence, they can estimate the consequences of their choices and select the best compromise solution [8]. Moreover, because of the complexity of the problem, the uncertainty of parameters is not modeled in many researches [9]. However, the impressive effects of the probabilistic nature of such parameters on the optimization results make it necessary for the planners to employ an effective method to consider the effect of uncertainties. To this aim, various approaches are presented, like: CC optimization [10], robust optimization [11], CVaR method [12], as well as stochastic programming [13]. The planners want to specify their decision variables in a robust and flexible way, to optimally overcome the uncertainties.

Recently, the importance of smart grid and its advantages and challenges, as well as the features and components of a future smart grid are highly concentrated [32]. In the smart grid environment, electricity customers will play a very important role by participating in the DR programs. DR programs persuade customers to change their consumption pattern when they are called. High utilization of distributed energy resources, including DR and DERs, are focused as the main activities of the future power systems [33]. Recently, DR programs have been examined by many studies due to their high benefit potential [34]. The role of DR in the future smart grids, its issues and also its future trends are presented in [35].

As it is known, distribution systems have some normally open, as well as normally close switches. Due to the variability of the loads, the switching operations can operationally have an important effect, because they can change the configuration of the system. Releasing the grid capacity in both the transmission and distribution systems, as well as the substations, are some of the benefits of DSR. Therefore, the DSR can be incorporated with the DEP problem to bring some advantages by releasing the capacity of the system [36].

Nowadays, high penetration of DERs is interested worldwide. However, there are some issues like thermal limits and protection issues that have restricted DERs' penetration level [37]. Hence, DERs should optimally be allocated, in order to overcome such problems. Although the site of DER units is determined by the owners, but their decisions will be affected, if efficient policies are designed by the DISCO. Picciariello et al. [38] investigated the effect of distribution tariffs on the investment decisions.

Recently, the utilization of the SoS has been interested, due to its managerial benefits and also its ability to efficiently model the behavior of independent systems. As there are some autonomous and independent entities in the distribution system, the behavior of them can be modeled by the SoS. The SoS is a popular approach for increasing the system abilities to overcome the management issues and system challenges [39]. Indeed, the SoS contains some heterogeneous constituents that are cooperating with each other for a common aim [40]. Therefore, the autonomous systems of the SoS, have interoperability and they can exchange a limited data. More details of the SoS are provided in section 2.

Consequently, there are different autonomous players in the distribution systems who can have interoperability with each other, while they have their own objectives. The presence of a comprehensive framework to model these interactions in an optimal manner to satisfy all the players should be investigated.

Table I chronologically categorizes the selected researches that addressed the planning of distribution systems. The specifications of this paper are presented in the last row of the table. In this paper, the DEP and DSR are integrated, while the potential of DERs and DR programs are considered. Dispatchable (diesel engine, gas turbine and fuel cell) and non-dispatchable (wind turbine) DERs are considered as the portfolio of the PI. The simplified wind power generation model [41] is used here to model the generation pattern of wind turbines. According to this model, wind turbines are modeled with some steps that have high accuracy for various geographical conditions. The PI will invest on DERs to gain benefits by selling the generated power. Furthermore, DRP is a new market player who will purchase DR capacities from the responsive customers and negotiate with the DISCO to sign a DR contract to sell these potentials in order to maximize its profit. Hence, the DISCO, PI and DRP are three independent and autonomous entities with separate objective functions; but they have interoperability and can share some variables. The aim of the PI and DRP is to maximize their own benefits, while from the DISCO point of view; the problem is a multi-objective optimization problem (minimizing the total monetary costs and the EENS as a reliability index). The MOPSO algorithm is applied to optimize the introduced non-linear mixed integer problem. DISCO should select the best solution among the Pareto-curve solutions, based on its policies. It should be mentioned that, by considering the risk level of the DISCO, the CC method is utilized to model the uncertainties of load levels in the future years. Furthermore, the PI and DRP should face with the uncertainties of the generation of DERs, and the available potential of DR, respectively. The CVaR method is employed to model the stochastic problems of the PI and DRP, by considering their separate confidence levels.

Briefly, the main contributions of this paper are as follows:

- the modeling of the DR by introducing the DRP as a new market player;
- the cooperation of the DSR with the DEP, while the potentials of DR and DERs are considered;
- proposing the SoS to model the independent behavior of the DISCO, PI and DRP;
- modeling the uncertainties: 1) by using the CC method from the DISCO viewpoint, and 2) by using the CVaR method from the PI and DRP viewpoints.

III. PROBLEM DESCRIPTION

A. *System of systems to contain DISCO, PI and DRP*

By restructuring the electric power delivery chain system, different players have been appeared to play a role in the system. Nowadays, in the real world, there are different entities who can have participation with their own goal that may be different or even conflicting with each other. Under this situation, the need for an efficient and comprehensive framework to contain all the players and satisfy them would be desired. The SoS framework is an approach to make it possible for all the entities to work with each other, while they have their own goals as an autonomous and independent system. The main features of an SoS are presented in [42-44] including: Autonomy, Belonging, Diversity, Connectivity and Emergence. These features are defined as the following.

1) Autonomy: The capability of the entities to decide and act as an independent system.
2) Belonging: The happiness of having a secure relationship. Regarding these references, the constituents cope with a paradox to act completely autonomously or to join a collective framework. By joining to the SoS, the constituents can balance their risks.
3) Diversity: the aggregation of different systems by the SoS in order to fulfill the social function. It is assumed that, the SoS will maximize its entities by connecting them by using the cooperation and collaboration.
4) Connectivity: The relationship among the constituents to enhance the SoS capabilities.
5) Emergence: A feedback for the autonomy and diversity to control the autonomy and heterogeneity for providing collaboration and functionalities.

Under the SoS framework, each entity will try to maximize its own profit. However, they should have cooperation with each other and share some variable. The optimum point of the SoS will determine the operating point of all the systems.

As mentioned, the SoS is a system containing a set of autonomous and heterogeneous systems with discrete and in some cases conflicting objective functions, who have interoperability and are aggregated for a common goal [42]. In addition to constant parameters and decision variables that are generally needed to model an entity, in the SoS model, adaptive parameters and shared variables are also required [45]. Adaptive parameters are constant and they are determined for one entity from other entities. For example, the

TABLE 1
TAXONOMY OF THE DEP

References	Distribution level	Mathematical modeling	Objective function	Horizon time [year/stage]	Optimization procedure	Problem specifications				
						Uncertainty	DR	DSR	DG	SoS
[14]	Primary	MINLP	MO	10 and 20	Artificial immune systems	✓				
[15]	Primary	MILP	SO	4	Branch and bound				✓	
[16]	Primary	MINLP	SO	10	GA					
[17]	Secondary	MINLP	SO	15	Tabu Search					
[18]	Primary	MINLP	MO	Horizon time	GA	✓			✓	
[19]	Primary	MINLP	SO	4	GA+OPF				✓	
[20]	Primary	MINLP	MO	4	Hybrid PSO, SFLA				✓	
[21]	Primary	MINLP	MO	5	GA	✓			✓	
[22]	Primary	MINLP	MO	20	Evolutionary algorithm	✓			✓	
[23]	Primary	MINLP	MO	3	ABC, Comprehensive learning PSO				✓	
[24]	Primary	MINLP	SO	10+ (until 2024)	Variable structure learning automata					
[25]	Primary	MINLP	MO	20	Non-dominated sorting GA	✓		✓	✓	
[26]	Primary	NLP	SO	1	GAMS (Using CONOPT solver)	✓			✓	
[27]	Primary	MINLP	MO	3	Modified PSO				✓	
[28]	Primary	MINLP	SO	20	Greedy randomized adaptive search procedure					
[29]	Primary	MINLP	SO	10 and 30	PSO	✓			✓	
[30]	Primary	MINLP	SO	5	GA	✓			✓ (PEV)	
[31]	Primary	MINLP	SO	Horizon time	Advanced PSO				✓	
This paper	Primary	MINLP	MO	4	MOPSO+ sensitivity analysis	✓	✓	✓	✓	✓

DISCO may specify the maximum penetration of DERs in each bus (an adaptive parameter of the DISCO), and the PI may determine the annual maximum investment (an adaptive parameter of the PI). Shared variables are at least common among two autonomous constituents. These variables reflect the influence of different conditions of independent constituents on each other. For example, the guaranteed purchasing prices of DERs are the shared variable between the DISCO and PI, while the DR prices are the shared variables between the DISCO and DRP.

Hence, DISCO, PI and DRP are three independent constituents that are modeled here by using the SoS, in order to achieve an optimal plan for DER expansion by the PI, as well as an optimal DR contract with the DRP. The PI and DRP are commercial agents with the aim of maximizing their profits. The aim of the DISCO is to upgrade the distribution system in the cost-effective and reliable way. Therefore, in the proposed problem: 1) the DISCO should determine and submit his/her adaptive parameters to the PI or DRP (like the maximum penetration of DERs), 2) the PI and DRP should send their adaptive parameters to the DISCO (like the maximum annual DER investment for the PI, and the maximum potential of DR for the DRP), 3) the DISCO determines the guaranteed purchasing prices for the PI, as well as the DR prices for the DRP, and 4) the PI and DRP specify the guaranteed power generation, and guaranteed available DR capacity, respectively, and send these data to the DISCO. It is noteworthy that, the DISCO sends the suggested prices for purchasing power from the PI, and DR from the DRP. Then, the PI and DRP will specify their strategies according to the received signals. Based on the decisions of the PI and DRP, the DISCO might change the suggested prices. This procedure should be repeated until the convergence of the solutions of the PI, DRP and DISCO to a common point. This solution is the optimum point of the SoS that determines the behavior of all the heterogeneous entities. Fig. 1 illustrates the framework of the proposed model.

B. The objective functions of the DISCO

The aim of the DISCO is to minimize the planning costs and the EENS. The monetary cost function is formulated as (1).

$$Min\left\{f_1\right\}=\left\{\sum_{y}\frac{1}{\left(1+i\right)^{y}}\times\left[C^{upg}\left(y\right)+C^{Loss}\left(y\right)+C^{tr}\left(y\right)+C_{DG}^{SoS}\left(y\right)+C^{DR}\left(y\right)\right]\right\} \tag{1}$$

in which,

$$C^{upg}\left(y\right)=\sum_{n_{cl}}\left\{UC\left(\chi_{n_{cl}}\left(y\right)\right)\times L^{n_{cl}}+C_{n_{cl}}^{f}\times z_{n_{cl}}\left(y\right)\right\},\forall\quad y\in\Psi \tag{2}$$

$$C^{Loss}\left(y\right)=\sum_{T}\left\{\sum_{n_f}\left[z_{n_f}\left(T,y\right)\times p_{n_f}^{loss}\left(T,y\right)\times t\left(T,y\right)\times LC\left(T,y\right)\right]\right\},\forall\quad y\in\Psi \tag{3}$$

$$C^{tr}\left(y\right)=\sum_{T}\left\{EC\left(T,y\right)\times t\left(T,y\right)\times p^{tr}\left(T,y\right)\right\},\forall\quad y\in\Psi \tag{4}$$

$$C_{DG}^{SoS}\left(y\right)=\sum_{b^P}\left[p_{b^P}^{QP}\left(y\right)\times\pi_{b^P}^{P}\left(y\right)\times\left(8760\right)\right],\forall\quad y\in\Psi \tag{5}$$

where,

$$p_{b^P}^{QP}\left(y\right)=\sum_{j^P}\left[p_{j^P,b^P}^{QP}\left(y\right)\right],\forall\quad b^P\in\mathrm{B}^P,\quad y\in\Psi \tag{6}$$

$$C^{DR}\left(y\right)=\sum_{b^R}\left[p_{b^R}^{QDR}\left(y\right)\times\pi_{b^R}^{DR}\left(y\right)\times\left(8760\right)\right],\forall\quad y\in\Psi \tag{7}$$

where, equation (2) is the upgrading cost of the feeders, (3) is the cost of energy losses, (4) is the cost to purchase energy from the upstream grid, (5) and (6) formulate the cost to motivate the PI to invest, and (7) is the contract cost with the DRP to provide a specified available capacity of DR. It should be noted that, according to (5), the DISCO ensures the PI to purchase its generated power, at least with the guaranteed prices. So, the PI could determine its optimal strategy according to these prices to be sure about the payback of its investment and to maximize the expected profit. Furthermore, regarding (7), the DISCO will negotiate with DRP to sign a contract to purchase DR. Therefore, the DRP should provide the specified available capacities of DR, and DISCO will pay to the DRP based on the contract between them.

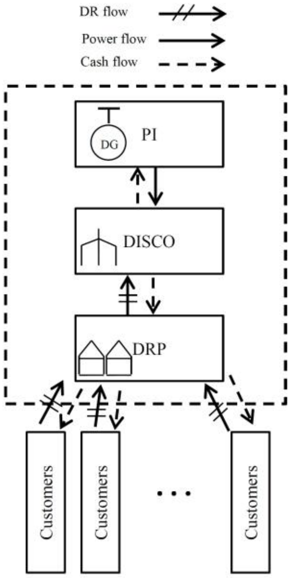


Fig. 1. The framework of the proposed SoS model

The next objective function of the DISCO is the reliability (EENS index) as expressed by (8).

$$Min\left\{ f_2 \right\} =$$
$$\sum_{T}\sum_{n_f}\left[\left(\lambda\left(\partial_{n_f}(y)\right)\times rp\left(\partial_{n_f}(y)\right)\times\frac{t(T,y)}{8760}\times L^{n_f}\right)\times pf_{n_f}(T,y)\times z_{n_f}(T,y)\right],\forall \;\; y\in\Psi \tag{8}$$

C. The objective function of the PI

The PI is a commercial agent who has an income by selling the power of DERs, while the cost terms are the investment and O&M costs of the DERs. The objective function of the PI to maximize is represented by (9)-(11).

$$Max \;\; \left\{ \begin{array}{l} \sum_{s^P}\sigma^P(s^P).f^P\left(y,s^P\right)+ \\ \theta^P\left[\xi^P-\frac{1}{1-\tau^P}\sum_{s^P}\sigma^P(s^P).\eta^P(y,s^P)\right] \end{array} \right\}, \qquad \forall \;\; y\in\Psi \tag{9}$$

where,

$$f^P\left(y,s^P\right)=$$
$$\sum_{y^*=1}^{Y-y+1}\frac{1}{(1+i)^{y^*-1}}\times\left\{\sum_{b^P}\left[\sum_{j^P}\left[A^P_{j^P,b^P}-B^P_{j^P,b^P}\right]\right]\right\}-C^{PI}+D^{PI},\forall \;\; y\in\Psi,\;\; s^P\in\Omega^P \tag{10-1}$$

$$A^P_{j^P,b^P}=p^P_{j^P,b^P}\left(y,s^P\right).\pi^P_{b^P}(y).(8760)$$
$$,\forall \;\; j^P\in\Xi^P,\;\; b^P\in \mathrm{B}^P,\;\; y\in\Psi,\;\; s^P\in\Omega^P \tag{10-2}$$

$$B^P_{j^P,b^P}=\alpha_{j^P,b^P}(y).\left(p^P_{j^P,b^P}\left(y,s^P\right).C^{O\&M}_{j^P}(y)\right).(8760)$$
$$,\forall \;\; j^P\in\Xi^P,\;\; b^P\in \mathrm{B}^P,\;\; y\in\Psi,\;\; s^P\in\Omega^P \tag{10-3}$$

$$C^{PI}=\sum_{b^P}\left\{\sum_{j^P}x^P_{j^P,b^P}\left(y,s^P\right).I^P_{j^P}\right\} \tag{10-4}$$

$$D^{PI}=\left\{\frac{1}{(1+i)^{Y-y+1}}\times\sum_{b^P}\left[\sum_{j^P}x^P_{j^P,b^P}\left(y,s^P\right).I^P_{j^P}.\frac{\Gamma_{j^P}-(Y-y+1)}{\Gamma_{j^P}}\right]\right\}$$
$$,\forall \;\; y\in\Psi,\;\; s^P\in\Omega^P \tag{10-5}$$

$$\eta^P(y,s^P)=\begin{cases}\xi^P-f^P\left(y,s^P\right), & \xi^P>f^P\left(y,s^P\right)\\ 0 \quad , & \xi^P\le f^P\left(y,s^P\right)\end{cases},\forall \;\; y\in\Psi,\;\; s^P\in\Omega^P \tag{11}$$

Equation (9) is the CVaR formulation of the objective function to consider the risk of uncertain parameters. Eqs. (10-1)-(10-5) formulate the objective function, where:

- the first term is the revenue of the sold power. It is calculated by considering the amount of sold power, the price of power and the generation duration.
- the second term is the O&M cost. It is computed by using the amount of power generated at bus “b^P” with “$j^{P,th}$” DG, the O&M cost of “$j^{P,th}$” DG and the effective generation duration.
- the third term denotes the investment cost. It is formulated by considering the size of “$j^{P,th}$” DG at bus “b^P”, as well as the installation cost of the “$j^{P,th}$” DG.
- the last term indicates the salvage value. It is formulated by considering the lifetime of the “$j^{P,th}$” DG, the passed working years, the size of “$j^{P,th}$” DG at bus “b^P”, as well as the value of the “$j^{P,th}$” DG.

It should be noted that, all the coresponding parameters and variables are defined in the “Nomencluture” section.

D. The objective function of the DRP

DRP wants to maximize its profit by purchasing DR potentials from responsive customers and selling them to the DISCO. DRP is also a commercial agent who has income according to the contract with the DISCO to provide the specified available DR capacities, while the cost of DRP is the persuasion cost of the customers to participate in DR. The objective function of the DRP can be formulated by (12)-(14).

$$Max \;\; \left\{ \begin{array}{l} \sum_{s^{DR}}\sigma^{DR}(s^{DR}).f^{DP}\left(y,s^{DR}\right)+ \\ \theta^{DR}\left[\xi^{DR}-\frac{1}{1-\tau^{DR}}\sum_{s^{DR}}\sigma^{DR}(s^{DR}).\eta^{DR}(y,s^{DR})\right] \end{array} \right\},\forall \;\; y\in\Psi \tag{12}$$

where,

$$f^{DP}\left(y,s^{DR}\right)=A^{DP}-B^{DP},\;\; \forall \;\; y\in\Psi,\;\; s^{DR}\in\Omega^{DR} \tag{13-1}$$

$$A^{DP}=\sum_{b^R}\left[p^{DR}_{b^R}\left(y,s^{DR}\right)\times\pi^{DR}_{b^R}(y)\times(8760)\right]$$
$$,\;\; \forall \;\; y\in\Psi,\;\; s^{DR}\in\Omega^{DR} \tag{13-2}$$

$$B^{DP}=\sum_{b^R}\left[\begin{array}{l} p^{DR}_{b^R}\left(y,s^{DR}\right)\times \\ \left[\varepsilon_{b^R}\times p^{DR}_{b^R}\left(y,s^{DR}\right)+\gamma_{b^R}\times\left(1-\omega_{b^R}\right)\right]\times 8760\end{array}\right]$$
$$\forall \;\; y\in\Psi,\;\; s^{DR}\in\Omega^{DR} \tag{13-3}$$

$$\eta^{DR}(y,s^{DR})=\begin{cases}\xi^{DR}-f^{DR}\left(y,s^{DR}\right), & \xi^{DR}>f^{DR}\left(y,s^{DR}\right)\\ 0 \quad , & \xi^{DR}\le f^{DR}\left(y,s^{DR}\right)\end{cases},\forall \;\; y\in\Psi,\;\; s^{DR}\in\Omega^P \tag{14}$$

Equation (12) is the CVaR formulation of the DRP’s objective function. The objective function is formulated by (13-1)-(13-3), in which:

- the first term denotes the income of the contracts to provide a specified amount of DR. It is calculated by considering the contract price, the amount of available DR capacity and the corresponding time duration.
- the second term is the cost of DR activation. In this equation, the DR price is modeled as a linear function that is extracted from [46]. In (13-3), ε_{b^R} [in $/MW^{2}h] and γ_{b^R} [in $/MWh] are constant coefficients, and ω_{b^R} is a coefficient in the range of [0-1] that shows the tendency of the customers to participate in DR [36]. The DR capacities and their time durations are also considered in this equation to model the DR cost.

E. The constraints of the DISCO

- The topology of the distribution system

Distribution networks should be operated radially and all the buses should be connected to the substations to prevent the islanding. The introduced method in [47] is employed to guarantee the validity of this constraint.

- Voltage thresholds

$$\Pr\left\{V^{min}\le V_m(T,y)\le V^{max}\right\}\ge 1-VDP,\;\; \forall \;\; m\in\Delta,\;\; T\in\Upsilon,\;\; y\in\Psi \tag{15}$$

where, $\Pr\{.\}$ is an operator to calculate the probability, and VDP is the voltage deviation probability. It should be noted that, VDP is determined by DISCO, to compromise between the probability of voltage deviation and the expected values of its other objectives. Indeed, VDP shows that how much risk is acceptable by the DISCO. If VDP is 0, it means that the DISCO is completely conservative and will take no risk.

- Current flow of feeders

$$\Pr\left\{\left|I_{n_f}\left(T,y\right)\right| \le I_{n_f}^{max}\left(y\right)\right\} \ge 1-LOP, \forall \;\; n_f \in \Lambda^f,\;\; T \in \Upsilon,\;\; y \in \Psi \qquad (16)$$

where, LOP is the probability of lines overload that has the meaning like VDP .

- Load balance

$$\mathrm{E}\left\{P_{sub}\left(T,y\right)\right\} = \mathrm{E}\left\{\sum_{m} p_m\left(T,y\right)\right\} + \mathrm{E}\left\{\sum_{n_f} p_{n_f}^{loss}\left(T,y\right)\right\}$$
$$-\sum_{b^R} p_{b^R}^{QDR}\left(y\right) - \sum_{b^P} p_{b^P}^{QP}\left(y\right),\;\; \forall \;\; T \in \Upsilon,\;\; y \in \Psi \qquad (17)$$

$$\mathrm{E}\left\{Q_{sub}\left(T,y\right)\right\} = \mathrm{E}\left\{\sum_{m} q_m\left(T,y\right)\right\} + \mathrm{E}\left\{\sum_{n_f} q_{n_f}^{loss}\left(T,y\right)\right\}$$
$$-\sum_{b^R} q_{b^R}^{QDR}\left(y\right) - \sum_{b^P} q_{b^P}^{QP}\left(y\right),\;\; \forall \;\; T \in \Upsilon,\;\; y \in \Psi \qquad (18)$$

where, $\mathrm{E}\{.\}$ is an operator to compute the expected values. These constraints represent that the total generated and consumed active and reactive powers are equal together.

- Financial resources

The DISCO may have a financial limitation for upgrading the distribution system.

$$\Pr\left\{pc\left(y\right) \le pc^{max}\left(y\right)\right\} \ge 1-ECP,\;\; \forall \;\; y \in \Psi \qquad (19)$$

In which, ECP is the probability that the expansion cost exceeds the maximum value.

F. *The constraints of the PI*

- Maximum capacity of each DER type in each bus

$$p_{j^P,b^P}^{P}\left(y,s^P\right) \le p_{j^P,b^P}^{DG,max}\left(y\right), \forall \;\; y \in \Psi,\;\; j^P \in \Xi^P,\;\; b^P \in \mathrm{B}^P,\;\; s^P \in \Omega^P \qquad (20)$$

- Generation capacity of DERs in each bus

$$\sum_{j^P} p_{j^P,b^P}^{P}\left(y,s^P\right) \le p_{b^P}^{DG,max}\left(y\right), \forall \;\; y \in \Psi,\;\; b^P \in \mathrm{B}^P,\;\; s^P \in \Omega^P \qquad (21)$$

- Total generation capacity of DERs in the network

$$\sum_{b^P}\sum_{j^P} p_{j^P,b^P}^{P}\left(y,s^P\right) \le p^{DG,max}\left(y\right),\;\; \forall \;\; y \in \Psi,\;\; s^P \in \Omega^P \qquad (22)$$

- The investment with the PI

$$\sum_{b^P}\sum_{j^P} x_{j^P,b^P}^{P}\left(y,s^P\right) \le x^{max}\left(y\right),\;\; \forall \;\; y \in \Psi,\;\; s^P \in \Omega^P \qquad (23)$$

- Pollution emission

The annual produced pollution should be maintained in a permissible range.

$$\sum_{b^P}\sum_{j^P} e_{j^P,b^P}\left(y,s^P\right) \le e^{max}\left(y\right),\;\; \forall \;\; y \in \Psi,\;\; s^P \in \Omega^P \qquad (24)$$

Eq (24) considers the pollution rate of different DG types to evaluate the generated pollution. According to this constraint, the total amount of generating pollution during a year should be maintained within the acceptable range.

G. *The constraints of the DRP*

The magnitude of DR is restricted by the DR capacity [36].

$$p_{b^R}^{DR}\left(y,s^{DR}\right) \le p_{b^R}^{DR,max}\left(y\right), \forall \;\; b^R \in B^R,\;\; y \in \Psi,\;\; s^{DR} \in \Omega^{DR} \qquad (25)$$

H. *Optimization procedure*

A two-layer procedure is used in this paper to solve the proposed problem. The decision variables of the first layer are lines reinforcement ($\chi_{n_{cl}}\left(y\right)$) and reconfiguration plan ($z_{nf}\left(T,y\right)$). Furthermore, the decision variables of the second layer are the shared variables of the SoS. The shared variables of the DISCO and PI, as well as the shared variable of the DISCO and DRP are determined in this layer. They include the guaranteed purchasing prices from the PI ($\pi_{b^P}^{P}\left(y\right)$), the guaranteed generation with the PI ($p_{b^P}^{QP}\left(y\right)$), the price of DR in each bus ($\pi_{b^R}^{DR}\left(y\right)$) and the guaranteed available capacity of DR in each bus ($p_{b^{DR}}^{QDR}\left(y\right)$).

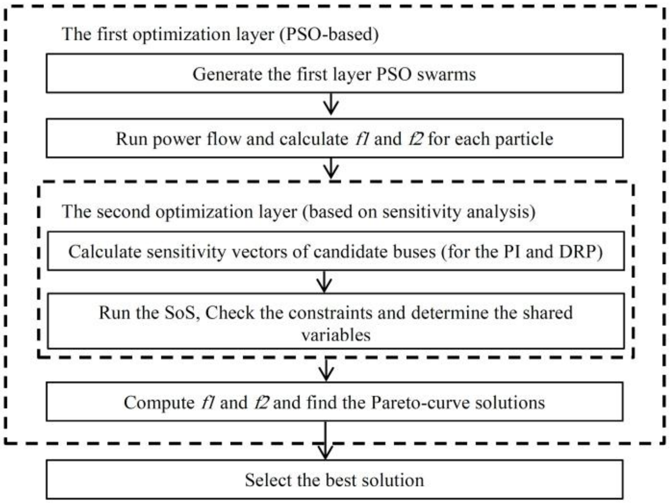


Fig. 2. The two-layer optimization procedure

The second layer is based on the sensitivity analysis, in which, the sensitivity indexes are defined as the following.

$$S_{b^P}^{DG}\left(T,y\right) = \frac{\Delta\left(PC\left(T,y\right)\right)}{\Delta\left(p_{b^P}^{QP}\left(y\right)\right)} \qquad (26)$$

$$S_{b^R}^{DR}\left(T,y\right) = \frac{\Delta\left(PC\left(T,y\right)\right)}{\Delta\left(p_{b^{DR}}^{QDR}\left(y\right)\right)} \qquad (27)$$

In these equations, $S_{b^P}^{DG}\left(T,y\right)$ is the sensitivity with respect to the installed capacity of DGs in bus "b^P", $PC\left(T,y\right)$ is the penalty cost of constraints deviations in the "T^{th}" time-period of each year, $\Delta(.)$ is the operator that denoted the changes of the relevant variables and $S_{b^R}^{DR}\left(T,y\right)$ is the sensitivity with respect to the DR capacity in the bus "b^R". $S_{b^P}^{DG}\left(T,y\right)$ and $S_{b^R}^{DR}\left(T,y\right)$ are (1×S) vectors, where, S indicates the number of discrete steps for the $\Delta\left(p_{b^P}^{QP}\left(y\right)\right)$ and $\Delta\left(p_{b^{DR}}^{QDR}\left(y\right)\right)$. It should be noted that, in the second layer, the DISCO determines the guaranteed purchasing prices from the PI and DRP. Then, on the basis of these price signals, the PI and DRP will determine their participation strategies. Based on the optimal strategies of the PI and DRP, the DISCO will modify the guaranteed purchasing prices to the next steps of the sensitivity analysis. This procedure should repetitively be continued until the convergence of the optimum points of all the entities. This convergence point is the solution point of the SoS that determines the behavior of all the autonomous systems.

Therefore, the first layer specifies the system configuration (based on the DSR variables), as well as the lines' reinforcement. The second layer determines the installed capacity of DGs and the available capacity of DR, as well as their guaranteed purchasing prices by using the SoS framework. Fig. 2 illustrates the flowchart of the optimization procedure.

IV. SIMULATION RESULTS

Two standard distribution systems are utilized to analyze the simulation results: the 33-bus and 118-bus, as introduced in [36] and [48], respectively. Firstly, the 33-bus standard distribution system is used. As it is mentioned, the DISCO models the load uncertainties by

TABLE II
ANNUAL COST AND EENS INDEX

Planning stages [year]	Planning cost (M$)	EENS (MWh)
1	0.61	5.11
2	0.61	5.02
3	1.25	5.60
4	0.86	5.58

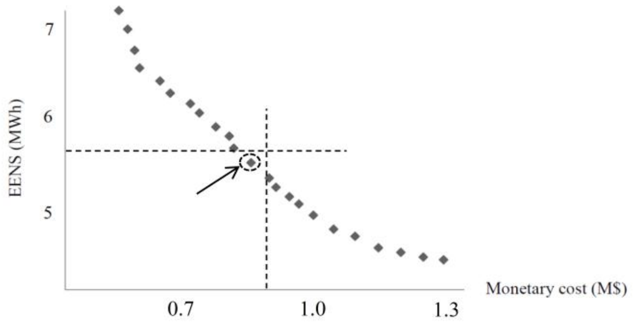


Fig. 3. Set of Pareto solutions for the last year

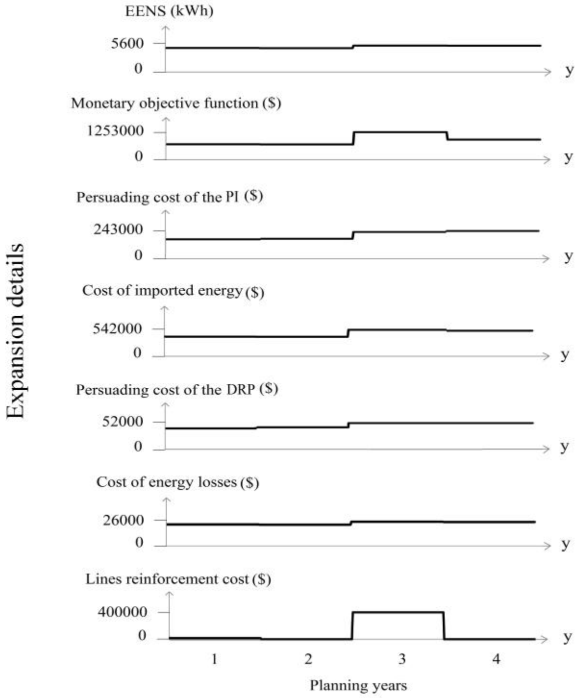


Fig. 4. The values of the cost terms and EENS indexes

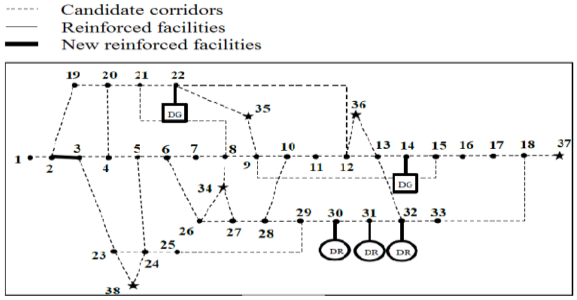
using the CC method. It is assumed that DISCO will accept the risk level of 15%. Furthermore, the PI faces with the generation uncertainties, and the DRP has the uncertainties regarding the DR potential. The CVaR method is employed to model the uncertainties of the PI and DRP, by considering 0.95 and 0.9 as the confidence levels of the PI and DRP, respectively.

Moreover, their risk factors are considered equal to 0.3. Various types of DERs are considered here including diesel engine, gas turbine, fuel cell and wind turbine. The generation of fossil-based DERs is deterministic, while, the uncertain generation of wind turbines is modeled by using the presented approach in [41] with four steps. The investment and operation cost data of the DERs are presented in [49]. The power factors of the diesel engine, gas turbine, fuel cell and wind turbine are 0.95, 0.95, 1.00 and 0.90, respectively. The correction factors in the optimization problem of the PI are 0.95. For the responsive load points, ε_{bR} and γ_{bR} are assumed 4 [$\$/\text{MW}^2\text{h}$] and 50 [$\$/\text{MWh}$], respectively. The annual financial limitations of the DISCO are 0.62, 0.62, 1.25 and 0.87 [M$] for the planning years.

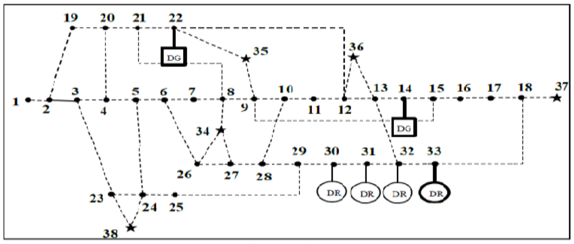
The pseudo-dynamic approach is used to solve the proposed multi-stage problem. As it is mentioned, the MOPSO is employed to find the Pareto solutions of the multi-objective problem. However, the planner should select one of the solutions, based on their policies and priorities. As pre-mentioned, the presented approach in [8] is utilized to select the best solution, based on the policies and limitations of the DISCO. In this paper, the maximum values of cost and reliability index are considered 0.90 (M$) and 5.7 (MWh), respectively. The features and data of the load (different energy sectors and load levels), and system specifications are provided in [36]. The peak load levels in the first year are assumed equal to 110 percent of the standard load levels of the 33-bus distribution system. The discount rate is 5%. According to assumptions, the candidate buses to install DERs are 8, 14, 22, 26, and responsive load points are 30-33. The maximum pollution emission is 4.5 and 5.5 [ton/day] in years 1-2, and 3-4, respectively. Finally, the life-time of fossil-based DERs and wind turbines are 10 and 15 years, respectively.

The optimum values of planning costs and reliability indexes as the objective functions of the DISCO are presented in Table II. As it is described, the DISCO has selected these solutions, among the Pareto set of solutions. Fig. 3 shows the Pareto solutions obtained through the MOPSO for the last planning year. As it is illustrated in Fig. 3, one solution is selected by the DISCO, based on its policies regarding the maximum limits of the objective functions. The value of each cost term and EENS index are shown in Fig. 4. Fig. 5 shows the optimum expansion plan, where the upgraded feeders, installed DERs and available DR capacities are indicated with bolded lines. PI invests to install DERs, based on the guaranteed purchasing prices from the DISCO that are presented in Table III. In addition, the types of installed DERs, as well as the expected generation pattern of each DER type (that are determined in the optimization problem of the PI), are shown in Table IV. Note that, the PI guarantees the total amount of power generation with different DER types, at each bus. It should be noted that, as the generation of the fossil-based DERs is deterministic, their generated power is proportional to the installed size of them; but for the wind turbines, due to the high uncertainties of generation, the installed capacity is more than the expected generation of them. It means, the PI can guarantee a specific capacity of generation, while it may install more. Fig. 6 shows the expected operation cost, income and benefit of the PI. Furthermore, DRP has a DR contract with DISCO to provide the specified capacities of DR. Tables V and VI present the contract prices between the DISCO and DRP, as well as the available DR potentials that are provided by the DRP. The expected annual cost, income and benefit of the DRP are illustrated in Fig. 7. As it is observed in Tables V and VI, the price of DR at bus 33 is higher than other buses, while the DR cost coefficients and customers' willingness are equal with each other. This is because of the less DR capacity in bus 33 than other responsive load points. Indeed, according to the objective function of the DRP (equation 13), the amount of DR capacity is effective in the expected profit of the DRP. It should be noted that the values of DR cost coefficients are effective in the profit function of the DRP. Therefore, the contract prices between the DISCO and DRP will change with respect to the different values of these coefficients. For instance, if ε_{bR} and γ_{bR} are 10 ($\$/\text{MW}^2\text{h}$) and 120 ($\$/\text{MWh}$) and all things remain constant as before, the contract prices will be increased to 140 at buses 30-32, and 196 at bus 33 in the last planning year. It is noteworthy that if the cost coefficients are too high (like $\varepsilon_{bR} = 15\ [\$/\text{MW}^2\text{h}]$) and $\gamma_{bR} = 200\ [\$/\text{MWh}]$), no agreement will be achieved between the DISCO and DRP. Moreover, the pollution constraint is one of the most important restrictions that can effectively change the optimal results of the SoS. For instance, if the pollution constraint in years 3 and 4 are 7.5 (ton/day), the PI will not install the new capacity of wind turbines, while, the capacity of diesel engines and gas turbines will be increased to 200 and 50 [kW], respectively (at both buses 14 and 22). Furthermore, the guaranteed prices at these buses will remain equal to 56 [$/kWh]. Therefore, if the pollution constraint is more restricted, the PI should invest to install more capacities of wind turbines, while the generation of other fossil-based DERs remains limited. In addition, the more limited pollution constraint will cause higher guaranteed prices, because, as pre-mentioned, due to the high uncertainty of wind power generation, the PI should install high capacities of wind turbines, while it can guarantee the lower generations. Hence, the PI will need higher guaranteed purchasing prices from the DISCO.

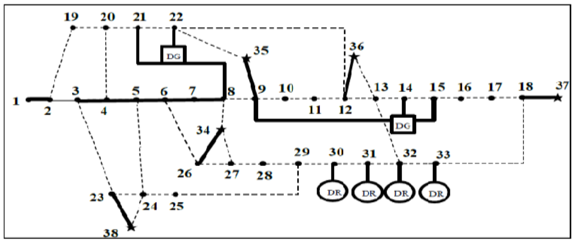
Finally, the 118-bus distribution system is utilized to study the results of the proposed problem. Five buses are considered to be developed since year 3 (buses 119-123). All the assumptions are provided in [50]. The guaranteed purchasing prices from PI, the generation patterns of DGs and the contract details with DRP (prices and available values) are provided in tables VII-X.



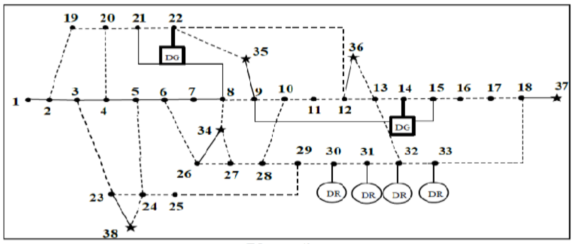
(Year 1)



(Year 2)



(Year 3)



(Year 4)

Fig. 5. Distribution system expansion plan

TABLE III
THE GUARANTEED PURCHASING PRICES

Planning stages [year]	Guaranteed prices [$/MWh]			
	Bus 8	Bus 14	Bus 22	Bus 26
1		56	56	
2		56	56	
3		84	56	
4		84	56	

TABLE IV
THE TYPES AND GENERATION PATTERNS OF THE GDS FOR THE PI

stages [year]	DER types	Generation [kW]			
		Bus 8	Bus 14	Bus 22	Bus 26
1	Diesel engine		150	150	
	Gas turbine				
	Fuel cell				
	Wind turbine		4	4	
2	Diesel engine		150	150	
	Gas turbine				
	Fuel cell				
	Wind turbine		6	6	
3	Diesel engine		200	150	
	Gas turbine		15		
	Fuel cell				
	Wind turbine		8	8	
4	Diesel engine		200	150	
	Gas turbine		15		
	Fuel cell				
	Wind turbine		10	10	

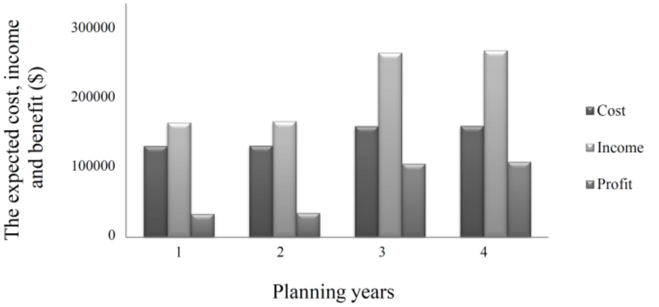


Fig. 6. The operational cost, income and profit of the PI

TABLE V
THE CONTRACT PRICES WITH THE DRP

Planning stages [year]	Guaranteed prices [$/MWh]			
	Bus 30	Bus 31	Bus 32	Bus 33
1	56	56	56	
2	56	56	56	84
3	56	56	56	84
4	56	56	56	84

TABLE VI
THE PROVIDED AVAILABLE DR POTENTIAL BY THE DRP

Planning stages [year]	DR capacity [kW]			
	Bus 30	Bus 31	Bus 32	Bus 33
1	30	22	31	0
2	30	22	31	8
3	34	25	35	9
4	34	25	35	9

V. CONCLUSIONS

This paper coordinated the DSR with the DEP problem, while the independent behavior of the DISCO, PI and DRP, and their interaction with each other are modeled by using the SoS. The DISCO, PI and DRP are autonomous systems with separate objectives. The proposed SoS model considers the aim of each independent system, as well as interoperability characteristics to find an optimal SoS solution that will determine the behavior of the whole system. The objective functions of the DISCO are to minimize the total planning cost, as well as the EENS index. The DISCO should cope with the load uncertainties in each year. By considering the risk level of the DISCO, the CC method is used to model the uncertainties of the DISCO. Moreover, the PI is a commercial agent who wants to maximize its profits. The PI receives guaranteed purchasing prices from the DISCO to install DERs.

Therefore, the PI should determine its generation pattern, in response

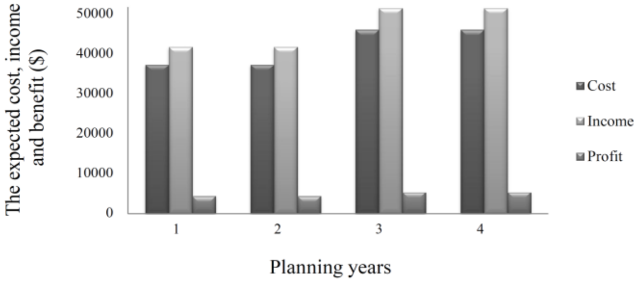


Fig. 7. The cost, income and profit of the DRP

TABLE VII
THE GUARANTEED PURCHASING PRICES

Planning stages [year]	Guaranteed prices [$/MWh]						
	Bus 2	Bus 28	Bus 42	Bus 50	Bus 74	Bus 102	Bus 111
1		56		56	56		56
2		56		56	56		56
3		56	56	56	56		56
4		56	56	56	56		56

TABLE VIII
THE TYPES AND GENERATION PATTERNS OF THE GDS FOR THE PI

stages [year]	DER types	Generation [kW]						
		Bus 2	Bus 28	Bus 42	Bus 50	Bus 74	Bus 102	Bus 111
1	Diesel engine		500		500	500		500
	Gas turbine		400		400	400		400
	Fuel cell							
	Wind turbine		5		5	5		5
2	Diesel engine		500		500	500		500
	Gas turbine		493		493	493		493
	Fuel cell							
	Wind turbine		7		7	7		7
3	Diesel engine		500	496	500	500		500
	Gas turbine		493	148	493	493		493
	Fuel cell							
	Wind turbine		7	12	7	7		7
4	Diesel engine		500	496	500	500		500
	Gas turbine		493	156	493	493		493
	Fuel cell							
	Wind turbine		7	14	7	7		7

TABLE IX
THE CONTRACT PRICES WITH THE DRP

Planning stages [year]	Guaranteed prices [$/MWh]			
	Bus 80	Bus 107	Bus 108	Bus 112
1				
2				
3				56
4				56

TABLE X
THE PROVIDED AVAILABLE DR POTENTIAL BY THE DRP

Planning stages [year]	DR capacity [kW]			
	Bus 80	Bus 107	Bus 108	Bus 112
1				
2				
3				36
4				36

to the purchasing signals. The CVaR method is utilized to model the DERs' generation uncertainties, by considering the confidence level of the PI. The DRP is also a commercial agent that is proposed as a market player to manage the DR potential. On one hand, the DRP should persuade customers to be ready to participate in DR and on the other hand, it should negotiate with DISCO to sign the best contract to sell the specified available capacity of DR. By considering the confidence level of the DRP, the CVaR method is used to model the uncertain behavior of customers. The proposed SoS framework proves that:

- Different independent players can share some of their variables with each other to have interoperability, while they independently optimize their own problems.
- All autonomous players can use their own desire methods to cope with their relevant uncertainties regarding their own independent risk level, and also use their favorable techniques to optimize their problem.
- Finally, the SoS optimum solution determines the behavior of the DISCO, PI and DRP as three independent and autonomous entities.

REFERENCES

[1] P. S. Georgilakis, and N. D. Hatziargyriou, "A review of power distribution planning in the modern power systems era: Models, methods and future research," *Electr. Power Syst. Res.*, vol. 121, pp. 89–100, Apr. 2015.

[2] A. Arefi, A. Abeygunawardana, and G. Ledwich "A new risk-managed planning of electric distribution network incorporating customer engagement and temporary solutions," *IEEE Trans. Smart Grid*, vol. 7, no. 4, pp. 1646 - 1661, Oct. 2016.

[3] M. Rostami, A. Kavousi-Fard, T. Niknam, "Expected Cost Minimization of Smart Grids With Plug-In Hybrid Electric Vehicles Using Optimal Distribution Feeder Reconfiguration," *IEEE Trans. Ind. Informat.*, vol. 11, no. 2, pp. 388-397, April 2015.

[4] A. S. B. Humayd, and K. Bhattacharya, "Distribution system planning to accommodate distributed energy resources and PEVs," *Elect. Power Syst. Res.*, vol. 145, pp. 1-11, Apr. 2017.

[5] A. Tabares, J. F. Franco, M. Lavorato, and M. J. Rider, "Multistage long-term expansion planning of electrical distribution systems considering multiple alternatives," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 1900-1914, May 2016.

[6] M. Ahmadigorji, N. Amjady, and S. Dehghan, "A novel two-stage evolutionary optimization method for multiyear expansion planning of distribution systems in presence of distributed generation," *Appl. Soft Comput.*, vol. 52, pp. 1098-1115, March 2017.

[7] S. Wen, H. Lan, Q. Fu, D. C. Yu, and L. Zhang, "Economic allocation for energy storage system considering wind power distribution," *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 644-652, March 2015.

[8] A. Zakariazadeh, S. Jadid, and P. Siano, "Stochastic multi-objective operational planning of smart distribution systems considering demand response programs," *Elect. Power Syst. Res.*, vol. 111, pp. 156–168, Jun. 2014.

[9] S. Dehghan, A. Kazemi, and N Amjady, "Multi-objective robust transmission expansion planning using information-gap decision theory and augmented -constraint method," *IET Gen. Transm. Distrib.*, vol. 8, no. 5, pp. 828–840, May 2014.

[10] B. Odetayo, J. MacCormack, W. D. Rosehart, and H. Zareipour, "A chance constrained programming approach to integrated planning of distributed power generation and natural gas network," *Elect. Power Syst. Res.*, vol. 151, pp. 197-207, Oct. 2017.

[11] S. Wang, S. Chen, L. Ge, and L. Wu, "Distributed generation hosting capacity evaluation for distribution systems considering the robust optimal operation of OLTC and SVC," *IEEE Trans. Sustain. Energy*, vol. 7, no. 3, pp. 1111-1123, Jul. 2016.

[12] M. Esmaeeli, A. Kazemi, H. Shayanfar, M. Haghifam, and P. Siano, "Risk-based planning of distribution substation considering technical and economic uncertainties", *Elect. Power Syst. Res.*, vol. 135, pp. 18-26, June 2016.

[13] J. Aghaei, M. Barani, M. Shafie-khah, A. A. Sánchez de la Nieta, and J. P. S. Catalão, "Risk-constrained offering strategy for aggregated hybrid power plant including wind power producer and demand response provider," *IEEE Trans. Sustain. Energy*, vol. 7, no. 2, pp. 513-525, Apr. 2016.

[14] E.G. Carrano, F.G. Guimarães, R.H. Takahashi, O.M. Neto, and F. Campelo, "Electric distribution network expansion under load-evolution uncertainty using an immune system inspired algorithm," *IEEE Trans. Power Syst.*, vol. 22, no. 2, pp. 851-861, May 2007.

[15] S. Haffner, L.F.A. Pereira, L.A. Pereira, and L.S. Barreto, "Multistage model for distribution expansion planning with distributed generation—Part I: Problem formulation," *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 915-923, Apr. 2008.

[16] S. Najafi, S.H. Hosseinian, M. Abedi, A. Vahidnia, and S. Abachezadeh, “A framework for optimal planning in large distribution networks,” *IEEE Trans. Power Syst*., vol. 24, no. 2, pp. 1019-1028, May 2009.

[17] A. Navarro, and H. Rudnick, “Large-scale distribution planning—Part I: Simultaneous network and transformer optimization,” *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 744-751, May 2009.

[18] V.F. Martins, and C.L.T. Borges, “Active distribution network integrated planning incorporating distributed generation and load response uncertainties,” *IEEE Trans. Power Syst.*, vol. 26, no. 4, pp. 2164-2172, Nov. 2011.

[19] H. Falaghi, C. Singh, M.R. Haghifam, and M. Ramezani, “DG integrated multistage distribution system expansion planning,” *Electr. Power Energy Syst.*, vol. 33, no. 8, pp. 1489–1497, Oct. 2011.

[20] M. Gitizadeh, A.A. Vahed, and J. Aghaei, “Multistage distribution system expansion planning considering distributed generation using hybrid evolutionary algorithms,” *Appl. Energy*, vol. 101, pp. 655–666, Jan. 2013.

[21] C.L.T. Borges, and V.F. Martins, “Multistage expansion planning for active distribution networks under demand and distributed generation uncertainties,” *Electr. Power Energy Syst.*, vol. 36, no. 1, pp. 107-116, March 2012.

[22] T. Jin, Y. Tian, C.W. Zhang, and D.W. Coit, “Multicriteria planning for distributed wind generation under strategic maintenance,” *IEEE Trans. Power Del.*, vol. 28, no.1, pp. 357-367, Jan. 2013.

[23] A.M. El-Zonkoly, “Multistage expansion planning for distribution networks including unit commitment,” *IET Gen. Transm. Distrib.*, vol. 7, no.7, pp. 766-778, July 2013.

[24] S.M. Mazhari, and H. Monsef, “Dynamic sub-transmission substation expansion planning using learning automata,” *Electr. Power Syst. Res.*, vol. 96, pp. 255–266, March 2013.

[25] A. Zidan, M.F. Shaaban, and E.F. El-Saadany, “Long-term multi-objective distribution network planning by DG allocation and feeders’ reconfiguration,” *Electr. Power Syst. Res.*, vol. 95, pp. 95-104, Dec. 2013.

[26] S.S. Al Kaabi, H.H. Zeineldin, and V. Khadkikar, “Planning active distribution networks considering multi-DG configurations,” *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 785-793, March 2014.

[27] J. Aghaei, M.K.M. Muttaqi, A. Azizivahed, and M. Gitizadeh, “Distribution expansion planning considering reliability and security of energy using modified PSO (Particle Swarm Optimization) algorithm,” *Energy*, vol. 65, pp. 398–411, Feb. 2014.

[28] M.M. Santos, A.R. Abaide, and M. Sperandio, “Distribution networks expansion planning under the perspective of the locational transmission network use of system tariffs,” *Electr. Power Syst. Res.*, vol. 128, pp. 123–133, Nov. 2015.

[29] R. Hemmati, R. Hooshmand, and N. Taheri, “Distribution network expansion planning and DG placement in the presence of uncertainties,” *Electr. Power Energy Syst.*, vol. 73, pp. 665–673, Dec. 2015.

[30] W. Yao, C.Y. Chung, F. Wen, M. Qin, and Y. Xue, “Scenario-based comprehensive expansion planning for distribution systems considering integration of plug-in electric vehicles,” *IEEE Trans. Power Syst*., vol. 31, no. 1, pp. 317-328, Jan. 2016.

[31] H. Saboori, and R. Hemmati, “Maximizing DISCO profit in active distribution networks by optimal planning of energy storage systems and distributed generators,” *Renew. Sustain. Energy Rev.*, vol. 71, pp. 365-372, May 2017.

[32] R. F. Arritt, and R. C. Dugan, “Distribution system analysis and the future smart grid,” *IEEE Trans. Ind. Appl*., vol. 47, no. 6, pp. 2343-2350, Nov.-Dec. 2011.

[33] N. Çiçek, and H. Deliç, “Demand response management for smart grids with wind power,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 625-634, Apr. 2015.

[34] H. S. V. S. K. Nunna, and D. Srinivasan, “Multi-Agent based transactive energy framework for distribution systems with smart microgrids,” *IEEE Trans. Ind. Inform.*, vol. 13, no. 5, pp. 2241-2250, Oct. 2017.

[35] R. Deng, Z. Yang, M. Y. Chow, and J. Chen, “A survey on demand response in smart grids: mathematical models and approaches,” *IEEE Trans. Ind. Inform.*, vol. 11, no. 3, pp. 570-582, Jun. 2015.

[36] H. Arasteh, M. S. Sepasian, and V. Vahidinasab, “An aggregated model for coordinated planning and reconfiguration of electric distribution networks,” *Energy*, vol. 94, pp. 786-798, Jan. 2016.

[37] F. Capitanescu, L. F. Ochoa, H. Margossian, and N. D. Hatziargyriou, “Assessing the potential of network reconfiguration to improve distributed generation hosting capacity in active distribution systems,” *IEEE Trans. Power syst.*, vol. 30, no. 1, pp. 346-356, Jan. 2015.

[38] A. Picciariello, C. Vergara, J. Reneses, P. Frías, and L. Soder, “Electricity distribution tariffs and distributed generation: Quantifying cross-subsidies from consumers to prosumers,” *Util. Policy*, vol. 37, pp. 23-33, Dec. 2015.

[39] B. Ge, K. W. Hipel, K. Yang, and Y. Chen, “A novel executable modeling approach for system-of-systems architecture,” *IEEE Syst. J.*, vol. 8, no. 1, pp. 4-13, Mar. 2014.

[40] M. Jamshidi, System of systems engineering: innovations for the twenty-first century, vol. 58. John Wiley & Sons, 2011.

[41] R. Karki, P. Hu, and R. Billinton, “A simplified wind power generation model for reliability evaluation”, *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 533-540, Jun. 2006.

[42] M. J. DiMario, J. T. Boardman, and B. J. Sauser, “System of Systems collaborative formation,” *IEEE Syst. J.*, vol. 3, no. 3, pp. 360-368, Sept. 2009.

[43] B. Sauser, J. Boardman, and D. Verma, “Systomics: Toward a biology of system of systems,” I*EEE Trans. Syst., Man, Cybernet.-Part A: Syst. Humans*, vol. 40, no. 4, pp. 803–814, Jul. 2010.

[44] B. Sauser, and J. Boardman, “Taking hold of system of systems management,” *Eng. Manag. J.*, vol. 20, no. 4, pp. 3–8, Dec. 2008.

[45] A. K. Marvasti, Y. Fu, S. DorMohammadi, and M. Rais-Rohani, “Optimal operation of active distribution grids: A System of Systems framework,” *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1228–1237, May 2014.

[46] D.T. Nguyen, M. Negnevitsky, and M. de Groot, “Pool-based demand response exchange—concept and modeling,” *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1677–1685, Aug. 2011.

[47] A. M. Cossi, R. Romero, and J. R. Mantovani, “Planning and projects of secondary electric power distribution systems,” *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1599-1608, Aug. 2009.

[48] K. Muthukumar, S. Jayalalitha, M. Ramasamy, and S. H. Cherukuri, “Optimal shunt capacitor allocation and sizing using harmony search algorithm for power loss minimization in radial distribution networks”, *Int. J. Develop. Res.*, vol. 4, no. 3, pp. 537-545, March 2014.

[49] V. Vahidinasab, “Optimal distributed energy resources planning in a competitive electricity market: Multiobjective optimization and probabilistic design,” *Renew. Energy*, vol. 66, pp. 354-363, Jun. 2014.

[50] http://facultymembers.sbu.ac.ir/vahidinasab/wp-content/uploads/2015/12/SOS_TII.pdf.

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