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A game-theoretic framework for active distribution network planning to benefit different participants under the electricity market

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Abstract: With the deregulation of the power sector, distribution system planning is transforming from the traditional integrated decision mode to the multiple-player-based decentralized paradigm. However, this could potentially cause an adverse impact on the performance of the system due to interest conflict of market players during operations. To address such an issue, this paper develops a game-theoretic framework for active distribution network planning under the electricity market. The interplay between the distribution utility (DISCO) and distributed generation investors (DGO) is formulated as a noncooperative, two-person-based Stackelberg game in which the DISCO, as the leader of the game, makes expansion of the grid to achieve the least-cost operation, and DGOs, as followers, pursue for maximizing their profits from DG investment based on the condition of the network structure. The real-time network reconfiguration has been considered as a new active management option in this work, and the uncertainties associated with DG are also taken into account. To solve such game-theoretic model effectively, a heuristic-based algorithm is also proposed and combined with the dynamic optimal power flow analysis. The numerical results on a 33-bus distribution network verify the validity of the proposed methodology.

Key words: Active distribution network, coordinated planning, game-theoretic approach, data clustering, heuristic algorithm

1. Introduction

Growing deficiencies of centralized bulk systems have led to the booming development of distributed generation (DG) technologies in the past decades. With the continuous integration of DG, distribution systems are evolving from the traditional passive networks to more complicated active distribution networks (ADNs) [1].

For distribution utility companies (DISCOs), DG units could bring about numerous potential benefits, such as investment deferral, loss reduction, and emission mitigation, [2], if they were properly used. As such, the DG allocation and its closely related problem of ADN integrated planning have been major focuses of research [3–9]. The former determines the siting and sizing of DG units in existing networks that best optimize system performance, whereas the latter mainly addresses the development of the network and RDG under the same framework. Based on different perspectives, a variety of planning models have been proposed considering different objective functions and these formulated models are solved by analytical, numerical, or heuristic approaches.

In existing studies, most of the discussions are based on a centralized context, where both network and

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DG units are vertically managed by a DISCO. However, such a condition is irrelevant to the electricity market environment today. In fact, with the unbundling of the power sector, new entities would emerge and participate in distribution investment (e.g., DG projects) as equal market players to the utility. Due to conflicts of interest between different individuals, the presented methods would become inapplicable.

To address this issue, a multiobjective DG planning model has been developed in [10] wherein the benefits of both the utility and DG owner (DGO) are taken into account. In [11], the DGO's rate of return was defined and incorporated as an additional constraint in the planning model of a DISCO. Moreover, a comprehensive decision-making method for coordinated ADN planning in the electricity market has also been proposed in [12].

Although the presence of these works provided considerable insights, the proposed models are primarily designed from DISCOs' perspective, and potential interplays among the utility and other entities are largely neglected. As a matter of fact, under a deregulated environment, the benefits/costs of a player are not only dependent on his/her own decision, but also on the strategies adopted by others. For the case of ADN, the DISCO is responsible for the construction (expansion) of feeders and substations, the outcomes of which determine the network capacity for DG accommodation; and reversely since the siting and sizing of DG leads to different operation performance of the system, the benefits of DISCO would be also affected, in turn, by the decisions of the DGO. Therefore, excluding the above interactivity in ADN planning may well cause failures in the acquisition of globally optimal solutions in real applications.

Game theory (GT) is an important mathematical methodology for studying decision-making problems with conflicts and collaborations between multiple rational individuals. According to [13], game-theoretic approaches can be categorized into cooperative and noncooperative paradigms depending on whether a binding agreement could be reached and the latter may be further divided into Cournot-type, Bertrand-type, and Stackelberg-type instances based on the rule of play. A well-formulated game model could generally converge to a Nash equilibrium representing a stable and optimal solution from which all the participants are most profited simultaneously without jeopardizing the interests of others.

Due to the suitability for characterizing behaviors in complex systems, GT has been widely utilized in smart grids and other social fields [14]. For example, the work in [15] presents a demand response strategy through GT from the perspective of users. The evolutionary dynamics of group interactions and their potential impact on the equilibrium of games are studied in [16]. Furthermore, the authors in [17] also investigated the issue of users' utility coupling due to information interaction and strategy popularity in evolutionary games on multilayer networks.

In this study, a game-theoretic framework is proposed for ADN planning under the deregulated environment. Compared to the works in [10–12], the main contributions of this paper are summarized as: 1) a Stackelberg game model is formulated to describe the interactive decision-making of DISCO and DGO that explicitly considers their divergent duties and interests; 2) a real-time network reconfiguration is introduced as a new active management scheme; 3) as the proposed model is not linear and concave, an evolutionary algorithm is employed to solve the problem effectively.

The rest of this paper is organized as follows. Section 2 discusses the modeling of active management schemes. The problem formulation and uncertainty representation are given in Section 3 and Section 4, respectively. The solution methodology is presented in Section 5, followed by the numerical study in Section 6. Finally, this work is summarized and some conclusions are drawn in Section 7.

2. Modeling of active management schemes

As a major difference to traditional distribution networks, the ADN adopts active management (AM) for its internal components that were once operated in a passive manner [1]. Here, the real-time network reconfiguration (RNR) is considered a new AM scheme along with the well-defined voltage regulation (VR) in the existing literature.

2.1. Voltage regulation

The voltage regulation in ADNs can be achieved through the on-load tap changer (OLTC) and/or power factor adjustment [3].

Control of the secondary voltage of the OLTC transformers can be realized by requiring the position of tap-changers to fall into the statutory range, as given by

$$T_{min}^{oltc} \leq T_t^{oltc} \leq T_{max}^{oltc} \qquad \forall t \tag{1}$$

As frequent tap-changing may cause severe equipment degradation, OLTC actions should not be performed more than the maximum number of times $\zeta_{\max}^{oltc}$ that can be tolerated in the prespecified interval

$$0 \leq \sum_t \zeta_t^{oltc} \leq \alpha_{max}^{oltc}, \tag{2}$$

where ζ_t^{oltc} is the 0-1 indicator, with $\zeta_t^{oltc} = 1$ if the position of OLTC is altered in period t, and $\zeta_t^{oltc} = 0$ if otherwise.

The control of the DG power factor must always fall within a permissible range, which can be represented by

$$\varphi_{\min} \leq \varphi_{g,t} \leq \varphi_{\max} \qquad \forall g \in \Omega_G, \forall t \tag{3}$$

2.2. Real-time network reconfiguration

Under ADNs, the prevalence of SCADA and advanced distribution automation enables DISCOs to fulfill remote control of tie/sectionalizing switches, which renders reconfiguration a viable tool for system management in real time [18]. In practice, the implementation of RNR is subject to the following frequency limit:

$$0 \leq \sum_t \left[\min \left(\sum_{(i,j) \in \Omega_{sw}} \left| s_{ij,t}^{sw} - s_{ij,t-1}^{sw} \right| 1 \right) \right] \leq \alpha_{\max}^{sw} \tag{4}$$

Moreover, the freedom of DISCOs to perform RNR should also be restricted as

$$\sum_{(i,j) \in \Omega_{sw}} \left| s_{ij,t}^{sw} - s_{ij,t-1}^{sw} \right| \leq \Delta S_{\max}^{sw} \qquad \forall t \tag{5}$$

where $\Delta S_{\max}^{sw}$ is the maximum number of switching actions permitted in each period.

In addition, the radiality constraint should be satisfied all the time in the grid, but is difficult to describe in mathematical form.

3. Problem formulation

In this study, the optimal planning of ADN in the electricity market is formulated as a Stackelberg game (SG) model wherein the DISCO acts as the leader and the private DGOs act as followers. SGs are hierarchical decision-making processes that perform based on a prespecified sequence [13]. It is selected here because in the unbundling environment the DISCO first forecasts the load growth and makes plans for network expansion, and, on the basis of such strategies, other players can then choose their own strategies (e.g., DG allocation for DGO) to maximize their interests. This forms a natural 'play of order' as is required by the formulation of SG.

The proposed model is composed of the upper-level (6)–(7) and lower-level (8)–(16), as given below:

$$\begin{aligned} Min\, C^{DIS} = & \left\{ \sum_{(i,j)\in\Omega_F} \sum_{a\in\Omega_A} [C_a^{IF} - Z_a^F/(1+d)^{TY}] l_{ij}\tau_{ij,a} + [C^{IB} - Z^B/(1+d)^{TY}]\varpi^{gsp} \right\} \\ & + \sum_{y=1}^{TY} [PR_s/(1+d)^y] \sum_{s=1}^{NS}\sum_{t=1}^{TH} r_t \left[\sum_{g\in\Omega_G} \rho_{y,t}^{dg} P_{g,y,s,t}^{dg} + \rho_{y,t}^{gsp} P_{y,s,t}^{gsp} \right. \\ & \left. + \rho_y^{los} \left(\sum_{(i,j)\in\Omega_F} P_{ij,y,s,t}^{lf} + P_{y,s,t}^{lsp} \right) + \rho_y^{ct} \left(e_y^{gsp} P_{y,s,t}^{gsp} + e^{dg} \sum_{g\in\Omega_G} P_{g,y,s,t}^{dg} \right) \right] \end{aligned} \tag{6}$$

$$\text{subject to: } \sum_{a\in\Omega_A} \tau_{ij,a} \in [0,1] \quad \forall (i,j)\in\Omega_F \tag{7}$$

$$\begin{aligned} MaxB^{DGO} = & \sum_{y=1}^{TY} [PR_s/(1+d)^y] \sum_{s=1}^{NS}\sum_{t=1}^{TH} r_t \sum_{g\in\Omega_G} \rho_{y,t}^{dg} P_{g,y,s,t}^{dg} \\ & - \sum_{g\in\Omega_G} [C^{IG} - Z^G/(1+d)^{TY}]\varpi_g^{dg} - \rho^{fu} \sum_{g\in\Omega_G} P_{g,y,s,t}^{dg} \end{aligned} \tag{8}$$

$$\text{subject to: } \varpi_{\min}^{dg} \le \varpi_g^{dg} \le \varpi_{\max}^{dg} \qquad \forall g\in\Omega_G \tag{9}$$

$$P_{i,y,s,t}^{gsp} + P_{i,y,s,t}^{dg} - P_{i,y,s,t}^{d} = \sum_{j\in\Omega, j\ne i} V_{i,y,s,t}V_{j,y,s,t}Y_{ij}\cos(\theta_{ij} + \delta_{j,y,s,t} - \delta_{i,y,s,t}), \qquad \forall i,j\in\Omega, \forall y, \forall s, \forall t \tag{10}$$

$$Q_{i,y,s,t}^{gsp} + Q_{i,y,s,t}^{dg} - Q_{i,y,s,t}^{d} = -\sum_{j\in\Omega, j\ne i} V_{i,y,s,t}V_{j,y,s,t}Y_{ij}\sin(\theta_{ij} + \delta_{j,y,s,t} - \delta_{i,y,s,t}), \qquad \forall i,j\in\Omega, \forall y, \forall s, \forall t \tag{11}$$

$$0 \le \sqrt{(P_{y,s,t}^{gsp})^2 + (Q_{y,s,t}^{gsp})^2} \le (\varpi_0^{gsp} + \varpi^{gsp}) \qquad \forall y, \forall s, \forall t \tag{12}$$

$$\left| P_{y,s,t}^{gsp} - P_{y,s,t-1}^{gsp} \right| \Big/ r_t\omega_{\max}, \qquad \forall_y, \forall_s, \forall t \tag{13}$$

$$0 \le P_{g,y,s,t}^{dg} \le \varpi_g^{dg} \qquad \forall g\in\Omega_G, \forall y, \forall s, \forall t \tag{14}$$

$$V_{\min} \le V_{i,y,s,t} \le V_{\max}, \qquad \forall \in Omega, \forall y, \forall s, \forall t \tag{15}$$

$$0 \le I_{ij,y,s,t} \le \sum_{a \in \Omega_A} \tau_{ij,a} I_{a,\max} \ \forall (i,j) \in \Omega_F, \forall y, \forall s, \forall t \tag{16}$$

The objective of a DISCO for overall cost minimization is described in Eq. (6). It includes 2 parts: (1) the investment costs for feeder rewiring and transformer upgrade, and (2) the variable costs of the ADN, which are attributed to energy procurement, energy losses, and generation emissions. Each term in the operation procedure is computed for the entire simulation period that considers all the scenarios (with different probabilities), all the hours in each day, and all the years. These costs have been converted to the year of investment by using the factor $1/(1+d)^y$, where d is the discount rate. It is also noted that, as the candidate resources of concern correspond to the different length of service-life, their residual value at the end of the planning horizon must be deducted from the investment costs. For the upper-level constraints, Eq. (7) stipulates that only 1 type of feeder conductor can be used for each right-of-way.

The upper-level optimization determines the usage of feeder conductors ($\tau_{ij,a}$) and transformer upgrade (ϖ^{gsp}) in the planning phase; moreover, it also calculates the optimal scheduling of DG units ($P^{gsp}_{y,s,t}$, $P^{dg}_{g,y,s,t}$) and setting of AM schemes (T^{oltc}_t, $\varphi_{g,t}$, and $s^{sw}_{ij,t}$) as decision variables for the operation phase.

The decision-making of the DGO is described in the lower level. The objective for maximization in Eq. (8) represents the total net benefits created by DG projects. The first term computes the expected revenues from selling energy to a DISCO and the second one represents the investment costs of DG. Eq. (9) defines the boundaries of DG penetration at each bus. The constraints for the active/reactive power balance are given by Eqs. (10) and (11). Constraints (12) and (13) enforce that the power injection from an external grid will not exceed the substation capacity, and not change sharply to guarantee the stability of the system. The dispatch level for DG units is constrained by their installed capacity, which is given by Eq. (14). Eqs. (15) and (16) also assure that the nodal voltage and carrying current in the feeders will remain within their permissible limits. In addition to the above constraints, it is worth noticing that the limitation related to AM should be considered as well, which has been introduced in Section 2. The lower-level model determines the optimal siting and sizing of DG units, ϖ^{dg}_g being the only decision variable.

4. Handling of uncertainties

In practice, the power output of DG units tends to exhibit stochastic characteristics due to possible mechanical failures as well as uncertainties associated with fuel supply. This is more particularly the case for renewable-based DG. In ADN planning, such uncertainties are normally captured in model formulation using a scenario-based approach [9]. However, incorporating all the possible scenarios would result in severe complexity and computational burden for solving the model. Hence, different types of techniques [19,20] have been used to reduce the number of input scenarios to an acceptable level while retaining the intrinsic value of the original information.

In this study, we use a well-known data clustering technique, fuzzy C-means [21], to achieve the above goal. Such a method can divide a substantial amount of original data into different groups (clusters) according to their perceived similarity. This is done via an optimization procedure whereby the clusters are searched so that the mean square distance from the original data to the synthesized clusters is minimized. The center of each cluster is regarded as that which could best represent all the individuals in this set. Following this method, the redundant scenarios can be effectively eliminated and only those with valuable information will be retained.

In our case, a matrix including power output curves of DG units across the planning horizon creates the set of used data. If we assume the outputs of DG at different sites are distributed independently, the probability of occurrence assigned to each refined scenario PR_s yields

$$PR_s = N_s/N_T, \tag{17}$$

where N_s denotes the number of data sets falling into cluster s, and N_T represents the total number of original input scenarios.

5. Solution methodology

The Stackelberg game model formulated above belongs to a nonlinear bi-level programming problem (NBLPP). As NBLPP has been proven to be strongly NP-hard in mathematics [22], the traditional solution strategy is to transform it into an equivalent single-level optimization problem, and then manage it by commercial solvers.

Such a transformation is typically implemented using the duality [23] or the Karush–Kuhn–Tucker (KKT) conditions [24]. However, for both techniques, it is required that the primal problem be strictly continuous and convex. To satisfy this condition, the AC power flow constraints (Eqs. (10) and (11)) must be linearized if using the duality theory. However, as such an approximation would distort the correct economic signals, the final decision obtained could be suboptimal in some occasions. Alternatively, if resorting to KKT conditions, the complementarity terms introduced would make the problem nonconcave. To examine the optimality of the solution, an ex-post facto iterative test becomes necessary. As a result, the computation burden would be largely increased for solving the problem and even becomes intolerable if the system scale is large.

In view of the above problems, an evolutionary algorithm, artificial bee colony (ABC) [25], is employed along with the multiperiod optimal power flow to solve the proposed model. In this method, the planning decisions of the DISCO and DGO are optimized using the ABC, which is a meta-heuristic algorithm inspired by the intelligent foraging behavior of honeybee swarms in nature. The candidate solutions are customized with integer codification. For each decision proposed by the DISCO/DGO, the dynamic AC optimal power flow (DOPF) [26] will be computed to reveal the operational performance of the system. A fitness function $Fit(x)$ is defined to evaluate the quality of each plan, and is composed of the corresponding objective of the DISCO/DGO with a penalty term, $Fit(x) = OF + \sum_{c=1}^{nc} \lambda_c \omega_c b_c,$, where λ_c, ω_c, and b_c represent the 0/1 indicator, penalty weight, and severity metrics for violation, respectively, nc denotes the number of constraints in the model, and obviously $\sum_{c=1}^{nc} \omega_c = 1$.

The entire optimization procedure will be terminated until the difference of the objective function value in two consecutive iterations becomes smaller than the predefined tolerance level. The flowchart of the optimization is shown in Figure 1.

Since the presented method belongs to a heuristic approach, it does not require the convexity of the problem. Therefore, it is able to solve the bi-level programming model in any forms while retaining the accurate formulation of AC power flow.

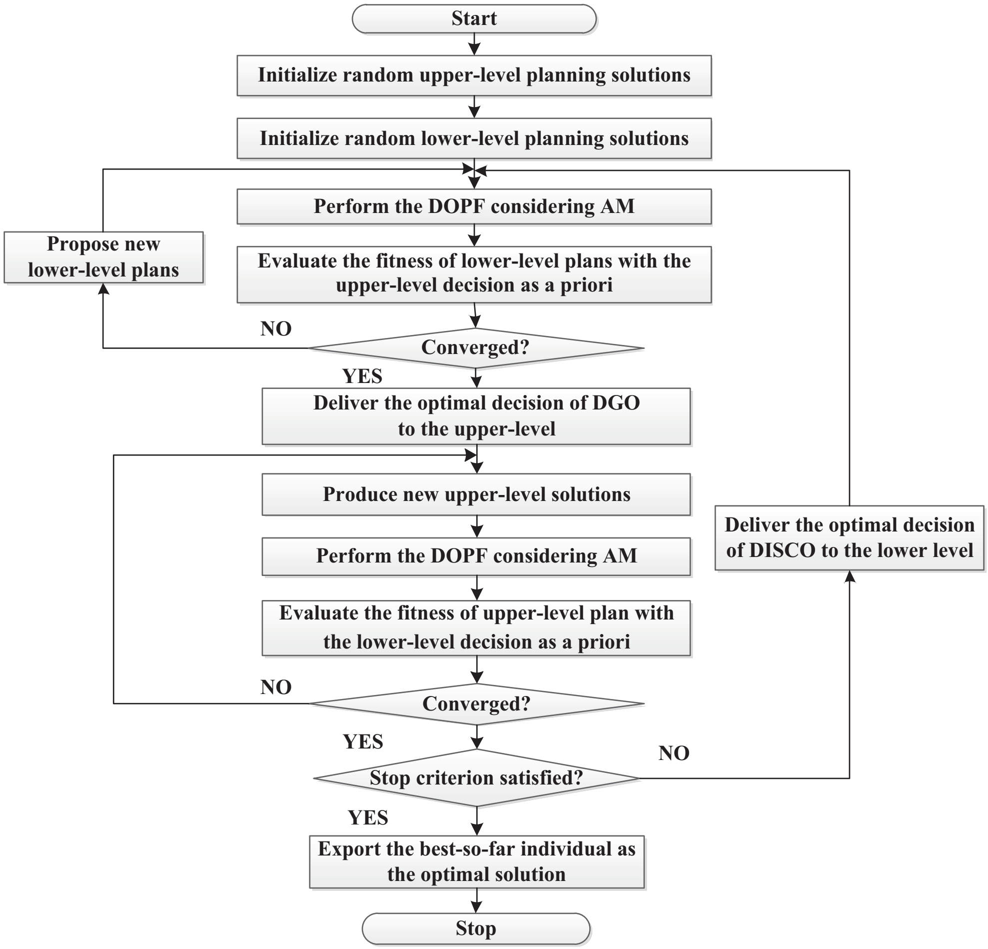

Figure 1. Optimization procedures based on hybrid ABC-DOPF algorithm.

6. Case study

6.1. Test system

The proposed methodology is tested with a 33-bus distribution system [27] as shown in Figure 2. The system is based on a medium-voltage 12.66 kV distribution grid and has peak demand of 3715 + j2300 kVA. The planning is supposed to be implemented in a time horizon of 10 years with a load growth of 3% and discount rate of 8%.

We herein consider 3 types of feeder conductors, with ampacity ratings of 335/445/610 A, respectively. The capacities of DG and the distribution transformers are discretized at definite steps of 0.1 MW and 5 MVA according to the commercial sizes. The candidate locations for DG connection are assumed to be {5, 6, 12, 17, 21} . The capacity that allows paralleling at each node is between 0.2 MW and 3 MW. The daily profiles of the load demand and wholesale market price are selected from [28]. To include the uncertainties of DG, we have considered different daily generation profiles (scenarios) using the real historical records. Then the fuzzy C-means method is applied to cluster the similar profiles. In our case, the number of clusters *NS* is taken to be 6. Other major data that are used in this study are shown in Table 1.

The simulation is programmed in the MATLAB environment.

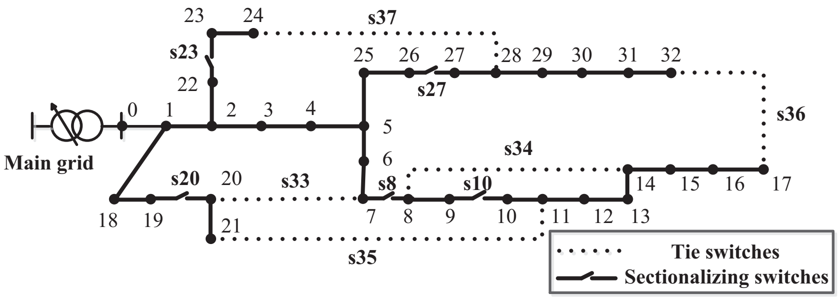

Figure 2. The 33-bus distribution system.

Table 1. Simulation parameters.

ρ^{dg}	\$13.5 cent/kWh	$\Delta S^{sw}_{\max}$	4 actions/time
ρ^{los}	\$9.8 cent/kWh	$\varphi_{\min}/\varphi_{\max}$	0.95(lagging)–0.95 (leading)
ρ^{ct}	\$25 /t	Toltc min/Toltc max	±10% (p.u.), 0.0125 p.u./step
ρ^{fu}	\$8.0 cent/kWh	V_{min}/V_{max}	±5% (p.u.)
e^{dg}	0.25 kg CO_2/kWh	$\alpha^{oltc}_{\max}$	6 times/day
e^{gsp}	0.93 kg CO_2/kWh	$\alpha^{sw}_{\max}$	12 times/day

6.2. Results and analysis

To demonstrate the effectiveness of the proposed methodology, we compare the results with the scenarios of integrated planning (IP) and uncoordinated planning (UP). IP represents the centralized planning paradigm, where the planning of network and DG units is optimized simultaneously, and UP refers to a type of independent decision-making mode, where the upper-level submodel is solved irrespective of the possible RDG insertions and the DGO makes the decisions with the current network capacity as the baseline. IP and UP are considered here because they are widely applied in real practice. The optimization results for all these cases are shown in Table 2.

Table 2. Optimal solutions under different planning paradigms.

		IP	UP		Bi-level	
		DISCO	DISCO	DGO	DISCO	DGO
DG (MW)	Bus 5	1.4	-	1.5	-	1.2
	Bus 6	0.8		0.5		0.7
	Bus 12	0.3		0.3		0.5
	Bus 17	0.2		0		0
	Bus 21	0.2		0.2		0.4
Network expansion* (M \$)		0.07	0.12	-	0.15	-
Power purchase (M \$)		3.15	2.39	-	2.98	-
Energy losses (M \$)		0.10	0.36	-	0.19	-
Carbon emissions (M \$)		0.47	0.78	-	0.51	-
Total costs (M \$)		3.79	3.65	-	3.83	-
DG investment* (M \$)		0.33	-	0.28	-	0.32
DG operation (M \$)		0.95	-	0.56	-	0.79
Electricity sale revenue (M \$)		1.89	-	1.11	-	1.62
Net benefits (M \$)		0.60	-	0.27	-	0.51

*The residual value has been deducted

As observed, compared with the IP solution, the total system costs and the benefits of DG are both inferior in other cases. This demonstrates that, although deregulation of the power sector may promote market efficiency from an overall perspective, it would also lead to benefit losses for each player. This is consistent with the general knowledge that, in a noncooperative game, the equilibrium solution does not necessarily yield the maximal system-wide payoff.

Compared with the UP solution, the network cost is higher in the game-theoretic solution. To analyze the reasons for such differences, we examine the efficacy of RES usage under the 2 cases and present the results in Table 3. However, such a seemingly economical plan does not come for free for both DISCO and DGO. Due to the use of feeders with smaller capacities, the total DG penetration in the UP plan is lower than the game-theoretic solution. In a real situation, this would considerably decrease the anticipatory profits achievable by DGO and thus diminish the willingness for investing in DG projects. The lack of coordination would impose an adverse impact on the DISCO as well. As shown in Table 3, compared with the game-theoretic solution, both the energy losses and generation emissions are higher in the UP case. This is because the load demand is mainly supplied by the substation in such a system. Although selecting larger feeder conductors increases the investment cost to the DISCO, the profits of the DGO also become higher. Because such growth is more considerable than the loss of the DISCO, the proposed scheme is more attractive to the welfare of the entire society.

Table 3. DG contribution in the solutions of different planning models.

	IP	UP	Game-theoretic
DG capacity (MW)	2.9	2.5	2.8
DG production (10^4 MWh)	1.81	1.07	1.55
DGP* (%)	52.85	31.24	45.26

*DGP: Ratio of DG contribution to load consumption

Next, we aim to analyze the effect of AM on the planning results. To do so, 4 scenarios representing different AM schemes have been defined: #1: without AM; #2: VR only; #3: RNR only; and #4: VR+RNR. The evaluation results are given in Table 4.

Table 4. Contribution of DG under different AM schemes.

	#1	#2	#3	#4
DG capacity (MW)	1.7	2.6	2.1	2.8
DG production (10^4 MWh)	0.87	1.42	1.09	1.55
DGP (%)	24.43	39.91	31.82	45.26

Compared with the passive control (Case #1), the benefits created by DG are higher for all the cases if AM is in place. Although both the VR and RNR schemes may promote the energy contribution of DG in the ADN, the degree of improvement is found to be more promising in Case #2. Moreover, the results in Case #4 are superior to those in other cases. This implies that the combination of VR and RNR imposes a synergetic effect for adapting RDG operation up to the grid requirements in comparison with using them separately.

In this work, we have considered the uncertainties of DG production in our model formulation. To analyze such an effect, Figure 3 compares the optimization results with the case ignoring uncertainties, i.e. all the DG units are assumed to be 100% available.

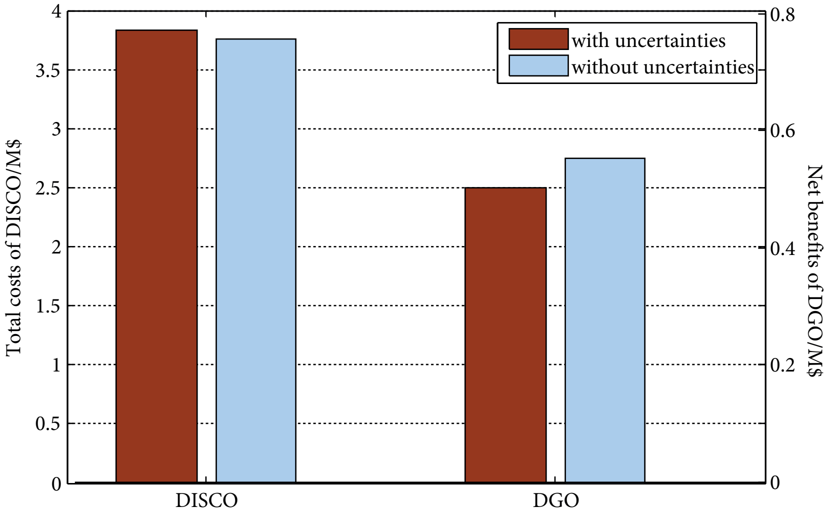

Figure 3. Comparison of DISCO/DGO's benefits with and without considering DG uncertainties.

As revealed, the uncertainties involved during DG operation have a direct impact on the obtained planning schemes. The anticipatory profits become less fascinating for both market players when such uncertainties are taken into account. This implies that potential risks of mechanical failures and fuel shortage could effectively offset the overall performance of the ADN and make the selected planning scheme less pronounced in actual implementations. As such, including the uncertainties of DG production is explicitly necessary.

6.3. Conclusion

In this study, a game-theoretic approach for ADN planning in the electricity market is proposed. We formulate the interrelated decision-makings of DISCO and DGO as a Stackelberg game in which the DISCO, as the leader of the game, makes expansion of the grid to achieve the least-cost operation, and DGOs, as followers, pursue for maximizing their profits from DG investment based on the network condition. The numerical results indicate that, in spite of the discrepancies existing, provided proper communication, all participants can obtain higher benefits from ADN projects in reference to the cases without strategic consociation. In this regard, the proposed method can be of great value from a regulatory point of view. In addition, it is also found that the potential benefits of DG are not only dependent on the network capacity, but also affected by the reactive power distribution in the system. The AM can be an effective means by which to increase DG penetration level in ADN without inducing extra costs. Although the RNR is found not as effective as VR, combining them could impose a synergetic effect compared with using any of them independently. Finally, it is observed that the uncertainties of DG during operations can have a direct impact on the effectiveness of final decisions. Therefore, considering such a factor in the ADN planning model is absolutely necessary.

Nomenclature

Ω_F	Set of right-of-ways
Ω_A	Set of conductor types
Ω_G	Set of DG buses
Ω_{SW}	Set of lines with switches
$\tau_{ij,a}$	0-1 variable for conductor selection
τ^{dg}	Installed capacity of DG
ϖ^{gsp}	Installed capacity of transformers
ϖ_0^{gsp}	Existed transformer capacity
P^{lf}	Power losses in feeders
P^{lsp}	Power losses in transformers
V	Magnitude of nodal voltage
I	Value of carrying current
T^{oltc}	Tap setting of OLTC
e^{gsp}/e^{dg}	Emission factor of grid/DG
φ	Power factor of DG units

l	Length of feeders in km
s^{sw}	Energized/disenergized status of lines with remote switches
$C^{IF}/C^{IB}/C^{IG}$	Investment cost of feeders /transformers/DG
$Z^F/Z^B/Z^G$	Residual value of feeders /transformers/DG
r	Duration of time period

ρ^{dg}	DG contract price
ρ^{gsp}	Wholesale market price
ρ^{los}	Energy loss price
ρ^{fu}	Fuel cost of DG units
ρ^{ct}	Emission tax rate
TH	Number of periods in 1 year
TY	Length of planning horizon
NS	Number of refined scenarios

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