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A Game Theoretical Approach for Sub-Transmission and Generation Expansion Planning Utilizing Multi- Regional Energy Systems

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ABSTRACT

This paper addresses a new method for sub-transmission and generation expansion planning utilizing multi-regional energy systems (RGESs). A competitive market design is also presented to capture interactions among RGESs investors in making optimal investment plans. Traditional and evolutionary game approaches are used for solving the investment and operational expansion planning problems to eliminate the traditional centralized planning and to enable competition among RGESs for power delivery using different bidding strategies. By using a fuzzy satisfying method (FSM), the evolutionary stability state (ESS) for each gaming option (i.e., scenario) is extracted and the ESS front is presented accordingly. Simulation results for a 9-bus system are finally presented to analyze the effectiveness of the proposed approach.

Keywords: Expansion Planning, Multi-Regional Energy System, Evolutionary Game Theory, Fuzzy Satisfying Method, Evolutionary Stability State.

NOMENCLUTURE

Indices

a	Mutual technological and locational scenario index, a={1,…,M}
b	Bidding strategy index, b={1,…,N}
i	RGES index, i={1,…,I}
k	RGES internal resources index, k={1,…,K}
p	Price level index, p={1,…,P}
j	Load point index, j={1,…,J}
t	Time index, t={1,…,LF_k}

l	The number of load level index, 1={1,…,L}

Parameter

ir	Interest rate
n_i	Technological and locational strategy of the i^{th} RGES
PF_{RGES}	Profit of RGES
I_{RGES}	Income of RGES
C_{RGES}	Cost of RGES
I_{INT}	Income of RGES from selling energy to local loads in regions
I_{NET}	Income from selling energy to upstream network
I_{DV}	Income from salvage value
C_{RGES}	Operational cost of RGES
C_{OC}	Maintenance cost of RGES's resources
C_{NET}	The cost of purchasing energy from the upstream network
C_{IC}	Total investment cost of RGES's resources
T	Duration of each load level
LF	Life Time
Π_{MC_k}	Marginal cost of the k^{th} resource of RGES
$\Pi^{\max}_{kNtl}$	Maximum bid in internal RGES's market in the l^{th} duration time of the t^{th} year
P_{kN}	The amount of energy sold by the k^{th} source to the upstream network
T_l	Duration of energy export from RGESs to upstream network
DV	Depreciation value
IC	Investment Cost
$\Pi_{kj}^{RGES_i}$	The selling energy price of the k^{th} resources of the i^{th} RGES to the j^{th} load point
P_{Load_j}	Power demand of the j^{th} load point
P_{transc_i}	Power exchanged between the i^{th} RGES and the upstream network
$P_{RGES_i}^{G}$	Generated power by the i^{th} RGES
P_{Loss}	Total network power losses
X(t)	Total installed capacity of the i^{th} RGES in the t^{th} year

$P_{k_{\max}}^{RGES_i}$	The maximum power of the kth internal resource of the ith RGES
$P_{Load_{\mathrm{Re}\,gion_i}}$	Total load in the ith region
$I_{kj_{\max}}$	Maximum line flow capacity of the shortest path between the kth resources and the jth load point
$S_j^{T_{\max}}$	Maximum transformer capacity of the jth load point (sub-transmission substation)
$P_G^{RGES_i}$	Total power generated in the ith RGES
λ	Reliability coefficient
P_j	The load amount of the jth load point
$\varnothing_{RGES_i}$	Set of all strategies made by the ith RGES
S_{RGES_i}	Strategy adopted by the ith RGES
TR_{kj}	Transmission right for transferring P_{kj} from internal resource k to the jth load point
C_{kj}	Total line installation cost
Variables	
Location	Location of internal resources of RGES
TECH	Technology of internal resources of RGES
Π_{kj}	Bidding price of the kth resources of RGES to the jth load point
$P_{kj}^{RGES_i}$	Energy amount of the kth resources of the ith RGES to the jth load point
$P_k^{RGES_i}$	The scheduled power of the kth internal resource of the ith RGES
I_{kj}	The amount of current flowing through the shortest path between the kth resources and the jth load point
$S_k^{\;RGES_i}$	The amount of power of the ith RGES

1. Introduction

In recent years, in order to increase efficiency, facilitate the use of renewable resources and eliminate environmental concerns, attract private sector participation and to use the potential of the demand side, planning of the power system towards smart grid structures has been initiated [1].Centralized traditional power network planning is no longer responsive and the need to provide new models and structures to facilitate the deployment of smart grid structure is essential. In addition, the new structure should facilitate the use of distributed generation resources (DGs), especially renewable ones [2]. To achieve these goals, new structures should be modeled and proposed. In the last decades, DGs and demand response have been widely used in electrical networks. The multiplicity and dispersion of these resources make the system's controllability and monitoring process difficult specially where a centralized entity is responsible to do so [3]. In order to solve the problems mentioned, the idea of using integrators such as microgrids and virtual power plants has been suggested [4]-[5]. However, the research treated in this section is mainly focused on the distribution sector. Thus, the proposal of a competitive model with regard to energy, market and decentralized decision-making infrastructure in generation and sub-transmission expansion planning seems essential. In order to overcome this deficiency, Regional Energy Systems (RGESs) are presented in this paper. RGESs aggregate distributed energy resources (DERs) and flexible loads with a central controller into advanced sub-transmission grid in a certain region. In the proposed method, it is possible to model the competition among investors of RGESs. Using traditional and evolutionary game theory and Fuzzy Satisfying Method (FSM), investors can explore different investment strategies by taking into account the decisions of other players and extract the equilibrium points of investment in each scenario.

1.1 Literature review

Extensive studies have been carried out in the electrical network expansion planning. Some studies have considered only traditional centralized expansion planning without DG units [6]-[7] while a number of researchers have included DG units in decision-making process [8]-[9]. In [10], the generation expansion problem at both national and regional levels has been considered with regard to reliability indices. However, authors failed to include transmission expansion planning as a complement to the aforementioned problem.

Although a significant amount of research has been reported in literature quantifying and optimizing the benefits of using an aggregator such as a microgrid in planning process [11]-[12], only a few studies have been dedicated to developing optimal investment models for integration of microgrids into power systems expansion plans. Some studies in this area have considered microgrid in islanded mode where decisions on expansion planning are made separately for microgrids and generation/transmission systems [12]-[13]. However, in today's restructured power systems, electrical energy is treated as a tradeable commodity meaning that the functions of energy generation or even distribution are open to private participation (e.g., participation of privately-owned microgrids or RGESs) and market prices are determined based on market forces and competition among the participants [14]-[15]. In such competitive environment, Generation Companies (GENCOs), Transmission Companies (TRANSCOs) and other players such as RGESs make investment decisions in a way to maximize their own profits [16]-[17]. Transmission expansion planning with demand side actions in the wholesale market has been studied in [18]. Economic expansion planning of sub-transmission grid and regional virtual power plant has been investigated in [19] with the aim of minimizing the sub-transmission system's cost. In the same work, the expansion planning problem has been formulated in a centralized format in which the benefits of the regional players and their competitions are neglected.

Also, different solution methods like multi-criteria optimization techniques have been developed to solve the multi-player network expansion planning problems [20]-[21]. For a multi-RGES with different owners such tools are highly needed to facilitate the decision-making process. Moreover, in such environments, each player with its own utility function has different strategies in doing the expansion plans (in terms of technology selection, sitting and sizing of devices, and bidding) which make expansion planning problems even more difficult. Fortunately, the game theory, as a powerful tool provides a promising way to solve the decision-making problems when multiple players pursue their maximum profits. Game theory is essentially the advanced type of the multi-objective optimization [22]-[23]. Through a Nash equilibrium, the game theory-based methods can make the players realize their optimal objectives in each scenario. In fact, the game theory has been applied to solve power system decision-making problems for many years in many research field [24]-[25].

1.2 Contribution of paper

In this paper, a game theoretical approach for sub-transmission and generation expansion planning is presented in presence of multiple RGESs. In this framework, RGESs can compete with each other to maximize their profit function, by choosing the right technology, sitting and sizing of their internal energy resources. In addition, in each planning scenario, RGESs will consider different bidding strategies. Given the huge diversity of search space, evolutionary game theory is also applied to examine the effect of different pricing strategies on the profits made by players [26]-[27]. Using the Fuzzy Satisfying Method (FSM) [28], the equilibrium point of the cross-price bidding for each scenario is determined, and by plotting these equilibrium points in a Nash front [29], different action plans are realized. Therefore, this paper extends the idea of the long-term multi-aggregator planning method presented in [5], [19] and [23] by proposing a new methodology to sub-transmission and generation expansion planning utilizing multi-RGESs with private ownership. As a whole, contributions of this paper can be summarized as follows:

- Introducing RGES as an independent new player in generation and sub-transmission expansion planning model. In such environment, an RGES could make optimal decisions while acting as a price-maker in local energy markets to maximize its profit,
- Applying evolutionary game theory concepts for investigating and solving mutual bidding strategies in a multi-player expansion planning problem,
- Decentralized decision making among different players by using a fuzzy satisfying method and utilizing an evolutionary-based stability state method to realize Pareto optimality.

1.3 Paper's structure

The rest of the paper is organized as follows. Problem statement together with definition of RGESs and their interaction with Sub-Transmission Expansion Planner (STEP) and ISO are introduced in Section 2. Problem formulation and the proposed methodology are given in Section 3. Numerical studies including the case study and the discussion of the results are presented in Section 4. Conclusions and further developments are discussed in Section 5.

2. Problem Statement and Definitions

In this paper, extension of sub-transmission and generation network in the planning horizon is addressed using RGESs and STEP as key players. Competition among RGESs are formulated based on decisions made in terms of type and location of internal resources and pricing strategy. The aim is to find the point(s) of equilibrium of the investment of the RGESs owners in a way not only to satisfy the network technical constraints, but also to supply the load economically in the planning horizon.

In Fig. 1, general overview of the proposed expansion-planning model is shown with n participating RGESs as key players who could adopt different strategies for technology, setting and sizing of internal resources, as well as different bidding schemes. Also, the characteristics and assumptions associated with each player are as below.

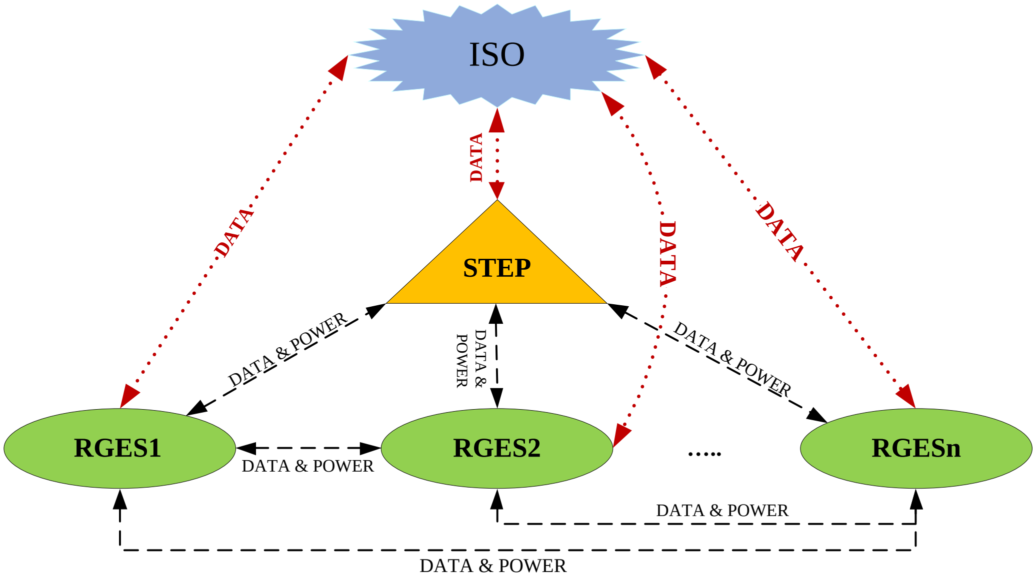

Fig. 1: General overview of the proposed multi-player expansion planning model

2.1 Regional Energy System (RGES)

The proposed RGES in this study is configured as an energy network in a specific geographic region that could host a variety of renewable and non-renewable energy sources as well as flexible loads representing a controllable entity into the power system. An RGES can be actively involved in expansion planning of sub-transmission networks by investing in capacity addition and/or installation of new internal DERs. An investor in RGES can be a single entity or a number of private shareholders. An agent is referred to a coalition participant seeks to maximize the profit of the RGES in the game. The main players in the model presented in this article are RGESs who put forth different investment scenarios, such as choosing the type of resource technology and location of resources, considering the strategies of other players. Also, in each scenario, they can investigate various bidding strategies to realize their market share. Finally, depending on different payoffs received at each strategy, optimal investment plans will be determined in a decentralized manner.

2.2 Sub-Transmission Expansion Planner (STEP)

In the proposed model, STEP is responsible for expansion planning and operation of sub-transmission grid. STEP also calculates the transmission right costs for supplying loads by the internal sources of RGESs and communicates data and power with the owners of RGESs. It uses the contractual path method [30] to calculate the transmission right. In this paper, the surcharges related to grid congestions and power losses are neglected.

2.3 Independent System Operator (ISO)

In the proposed model, ISO has three essential functions as follows:

a) Providing information such as forecasted load at each load center in the planning horizon and specifications of feeders, lines, network constraints, etc. to all players.

b) Checking network technical and security constraints

c) Doing the economic dispatch of generation facilities by minimizing the total energy purchase cost function as detailed in section 3.1.3.

2.4 Load points

In this paper, it is assumed that load points are concentrated in the out coming of the sub-transmission substation. Each load point can be supplied from the mains and/or by RGESs according to economic dispatch results. This means that local energy systems compete with each other in energy provision of each load point.

3. Problem Formulation and Solution Methodology

3.1 Problem Formulation

A decision-making process is called a game when decision-makers are pursuing their own maximum profits at the same time. Accordingly, game theory is developed to study the conflict and cooperation among rational decision-makers [23]. A game includes several elements among which the player, strategy, and payoff function are necessary. A typical sub-transmission and generation network with multiple RGESs is shown in Fig. 2. It is assumed that in each RGES, there are n_m load points and k_m internal DERs. STEP's typical network is shown with blue dashed lines and data interactions among entities are shown in black dotted lines.

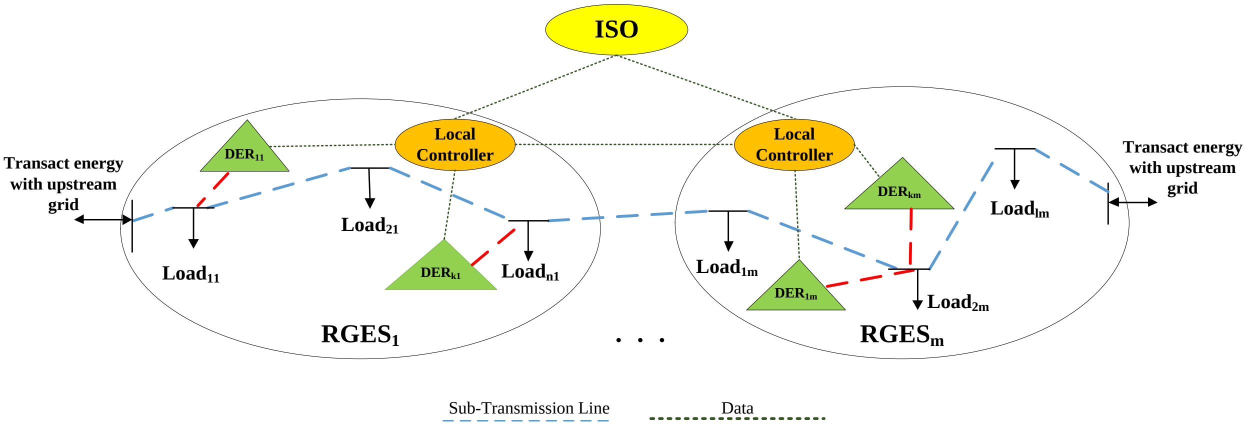

Fig. 2. Block diagram of an electrical network considering multi-RGES

3.1.1 Element of the game

1) *Player*: The RGESs are the players of the examined game. They have several strategies to practice in order to maximize their profit considering other player's strategies.

2) *Strategy*: The strategies or decision variables of each player are their corresponding internal resources technologies, their location (i.e., sitting in the local network) and bidding strategies in each technological and locational scenario. Technological and locational strategies are proposed in investment planning while mutual bidding strategies are

investigated in the operations scheduling phase. Limited by the physical environment and policies, the decision variables belong to specific strategic space, i.e.

$$S_{RGES_i} \in \left\{ \varnothing_{RGES_i} = \left\{ \left[Location_{1i}, ..., Location_{k_i} \right], \left[Tech_{1i}, ..., Tech_{k_i} \right], \left[\Pi_{1i}, ..., \Pi_{p_i} \right] \right\} \right\} \tag{1}$$

3) *Payoff functions:* In this paper, payoff function of each player is the profit that can be made during its life cycle. This function will be detailed in the next subsection. In order to get the payoff each player, many factors such as the income from selling power to the upstream network or end users, network policy, salvage value and the costs from initial invest, operation and maintenance as well as the energy not supplied cost should be considered.

4) *Evolutionary Stable Strategy (ESS):* Maynard Smith applied the concept of an evolutionary stable strategy/state (ESS) to examine the evolutionary processes where players adopt a strategy and then learn of its comparative success. The Nash Equilibrium (NE) is a concept within game theory that examines a non-cooperative game in which each player within the game is assumed to be aware of the strategies of the other players. Similarly, the ESS is an equilibrium refinement or modification of Nash equilibrium. An ESS strategy is essentially a Nash equilibrium within an artificially constructed zero-sum game in which each player chooses the same strategy while distinguishing between their own real payoff and the real payoff of their opponents throughout the game [31]. In this model, there are one or more ESSs for each technological and locational scenario. In fact, after proposing mutual technological and locational scenarios in the investment planning stage, different bidding strategies will be examined in an evolutionary game at the operations scheduling stage to minimize the total energy purchase costs and to determine the right capacity of RGES's resources. This process will be repeated over the next scenario to extract ESS of each technological and locational strategy.

3.1.2 Payoff of each player

The payoff of each player (RGES) is set to be the net present value of profit function of the corresponding player in its life cycle. The profit function of each player is the difference in income and expenses over its lifetime.

$$PF_{RGES} = I_{RGES} - C_{RGES} \tag{2}$$

The income and expense components of each player is explained below.

1) *Components of each player's income*

In presented model, net present value of RGES's income consists of three elements. The first term is the revenue made by selling energy to the load points within the regions, which is determined after the total cost of supplying energy minimization in each mutual bidding strategy, and determining the amount of allocated power/capacity of the internal DERs of the RGES. The second term in Eq. (3) represents the income made by selling extra power of RGES to external network at its marginal price. Net present value of salvage of RGES's internal DERs is the third term in Eq. (3).

$$I_{RGES} = I_{INT} + I_{NET} + I_{DV} \tag{3}$$

$$I_{INT} = \sum_{k=1}^{K} \sum_{j=1}^{J} (1+ir)^{-LF_k} \left(\sum_{t=1}^{LF_k} \sum_{l=1}^{L} \Pi_{kjtl} \times P_{kjtl} \times T_l \right) \tag{4}$$

$$I_{NET}=\sum_{k=1}^{K}\sum_{j=1}^{J}(1+ir)^{-LF_k}(\sum_{t=1}^{LF_k}\sum_{l=1}^{L}\Pi_{MC_k}\times P_{kNtl}\times T_l) \tag{5}$$

$$I_{DV}=\sum_{k=1}^{K}(1+ir)^{-LF}DV_k \tag{6}$$

2) *Components of each player's cost*

In presented model, net present value of RGES's costs consists of three elements. The first term is the total operational cost of RGES's resources. The second term is the cost of purchased energy from external grid in case that RGES's internal resources failed to deliver the scheduled energy. In this case the energy supplement must be purchased from the external grid by RGES at the maximum bidding price of RGES's internal market. The third term is the total investment cost of each internal resources of RGES.

$$C_{RGES}=C_{OC}+C_{NET}+C_{IC} \tag{7}$$

$$C_{OC}=\sum_{k=1}^{K}\sum_{j=1}^{J}(1+ir)^{-LF_k}(\sum_{t=1}^{LF_k}\sum_{l=1}^{L}OC_{kjtl}\times P_{kjtl}\times T_l) \tag{8}$$

$$C_{NET}=\sum_{k=1}^{K}\sum_{j=1}^{J}(1+ir)^{-LF_k}(\sum_{t=1}^{LF_k}\sum_{l=1}^{L}\Pi^{\max}{}_{kNtl}\times P_{kNtl}\times T_l) \tag{9}$$

$$C_{IC}=\sum_{k=1}^{K}\sum_{t=1}^{T}(1+ir)^{-t}\times(IC)_{tk} \tag{10}$$

3.1.3 Economic dispatch of energy sources

At operations scheduling stage, the total cost of supplying energy is minimized according to Eq. (11) subject to several technical constraints. By solving this optimization problem, the power share of different generation units in RGESs is determined in given bidding strategies of players and bid-quantity packages are framed, accordingly.

$$\min\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\Pi_{kj}^{RGES_i}\times P_{kj}^{RGES_i} \tag{11}$$

s.t.

- Power balancing constraint

$$\sum_{j=1}^{J}P_{Load_j}+\sum_{i=1}^{I}P_{transc_i}=\sum_{i=1}^{I}P_{RGES_i}^{G}+P_{Loss} \tag{12}$$

- Generation constraints

$$X_{RGES_i}(t)\le X_{RGES_i}(t+1) \qquad \forall i,t \tag{13}$$

Equation (13) states that the total installed capacity of the ith RGES in the coming year should not be less than the total installed capacity of the current year.

Also, in the proposed model, in order to allow competition among players, upper level and lower level of each RGES's resources in investment planning stage is as below;

$$0 \le P_k^{RGES_i} \le P_{Load_{Region_i}} \tag{14}$$

$$0 \le P_k^{RGES_i} \le P_{k_{Max}}^{RGES_i} \tag{15}$$

Equation (15) states that the allocation capacity of each internal source of RGESs should not exceed its maximum capacity.

- Transmission network constraints

$$\left|I_{kj}\right| \le \left|I_{kj_{\max}}\right| \qquad \forall i,t \tag{16}$$

$$\left|S^{RGES_i}\right| \le \left|S_j^{T_{\max}}\right| \qquad \forall i,t \tag{17}$$

- Adequacy of supply constraint

In this paper, the total installed capacity of the internal units of the RGES is assumed to be larger than the total estimated load in the planning horizon. In Eq. (18), λ is a numeric greater than one.

$$\sum_{i=1}^{I} P_G^{RGES_i} \ge \lambda.\sum_{j=1}^{J} P_j \qquad \lambda > 1 \tag{18}$$

3.1.4 Transmission right calculation

In this paper, contractual path method is used to calculate transmission right [30]. In fact, STEP as a responsible entity for planning and operation of sub-transmission grid, calculates transmission fee for supplying each load by internal resources of RGES using the following equation:

$$TR_{kj} = C_{kj}\frac{f_{kj}}{f_{l_{kj}}} \tag{19}$$

In Eq. (19), C_{kj} is the total investment cost for installing the line between contractual path between the kth internal resource of RGES and the jth load point. $f_{l_{kj}}$ is the total capacity of mentioned line and f_{kj} is the allocated capacity of the kth resources of RGES for supplying the jth load point via contracted path.

3.1.5 Evolutionary stability states solving algorithm

1) *Fuzzy satisfying method*

In this paper, fuzzy sets are defined for all calculated RGES' s profit function according to Eq. (20). Here it is assumed that maximum and minimum values of profit functions of each market participant (i.e., $PF_i^{\max}$ and $PF_i^{\min}$) can be predicted based on historical data. By taking the individual's profit range into account, the membership function $\mu(PF_i)$ for each objective function can be determined as below [28]:

$$\mu(PF_i) = \begin{cases} 0 & PF_i \le PF_i^{\min} \\ \dfrac{PF_i - PF_i^{\min}}{PF_i^{\max} - PF_i^{\min}} & PF_i^{\min} \le PF_i \le PF_i^{\max} \\ 1 & PF_i \ge PF_i^{\max} \end{cases} \qquad (20)$$

Minimum value of all membership functions for a specific set of bidding strategies represents the optimal value of that set. A set with larger minimum value of membership functions is more favorable, since it satisfies more objective functions in terms of individual optimum values. In case of multiple objective functions, the optimal solution (i.e., the equilibrium) can be realized as follows:

$$Max\,\psi = Max\left\{\min\left(\mu(PF)_i\right)\right\} \qquad i = 1,\ldots,M \qquad (21)$$

According to (21), optimal bidding strategies for all market participants would be a combination in which ψ has the highest value. The proposed method may reach only one EES or multiple ESSs for each scenario determined in the investment planning phase. Bidding constraints in a power system could be responsible for the existence of multiple ESSs [28].

2) ESS Front concept for decentralized decision-making [29]

Analysis of location for Pareto-optimal set and Nash equilibrium in the feasible region for a two-player game is provided in [32] with two generic objective functions $PF_1(u_1,u_2)$ and $PF_2(u_1,u_2)$, where player 1 and 2 control design variables are u_1 and u_2, respectively. This analysis uses rational reaction sets in the coordinate system of game variables, however does not provide any insight into changes in distribution and location of ESS once the control of variables or design authority are reassigned among players especially in an evolutionary game. Therefore, it is difficult to evaluate practically how ESS will change in different scenarios. The notion of the ESS front (Fig. 3) is introduced to bridge the gaps. The ESS front is considered in the coordinate system of objective functions $PF_1(u_1,u_2,\ldots,u_n)$ and $PF_2(u_1,u_2,\ldots,u_n)$ and is a set that consists of ESS.

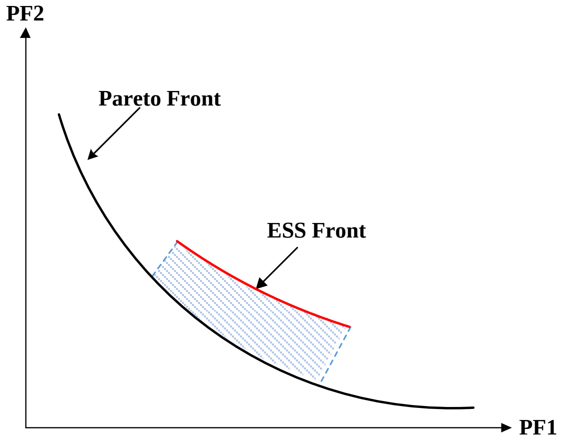

Fig. 3. Non-dominated Pareto front, dominated ESS front and the region between perfect centralized and perfect decentralized decision making

The Pareto- frontier identifies the design solutions assuming perfect centralization. Such solutions are optimal among all possible or neighboring solutions and obtained by optimizing all objective functions simultaneously. All solutions in between the two fronts correspond to those generated by changing assumptions in the game theory setting. So, given the optimization strategy defined for each player, we may expect a different location of the ESS relatively to the Pareto front, depending on the number of decision variables in specific scenarios.

3.2 Solution Methodology

The proposed two-stage algorithm for solving the sub-transmission and generation expansion planning problem in presence of multiple RGESs is shown in Fig. 4.

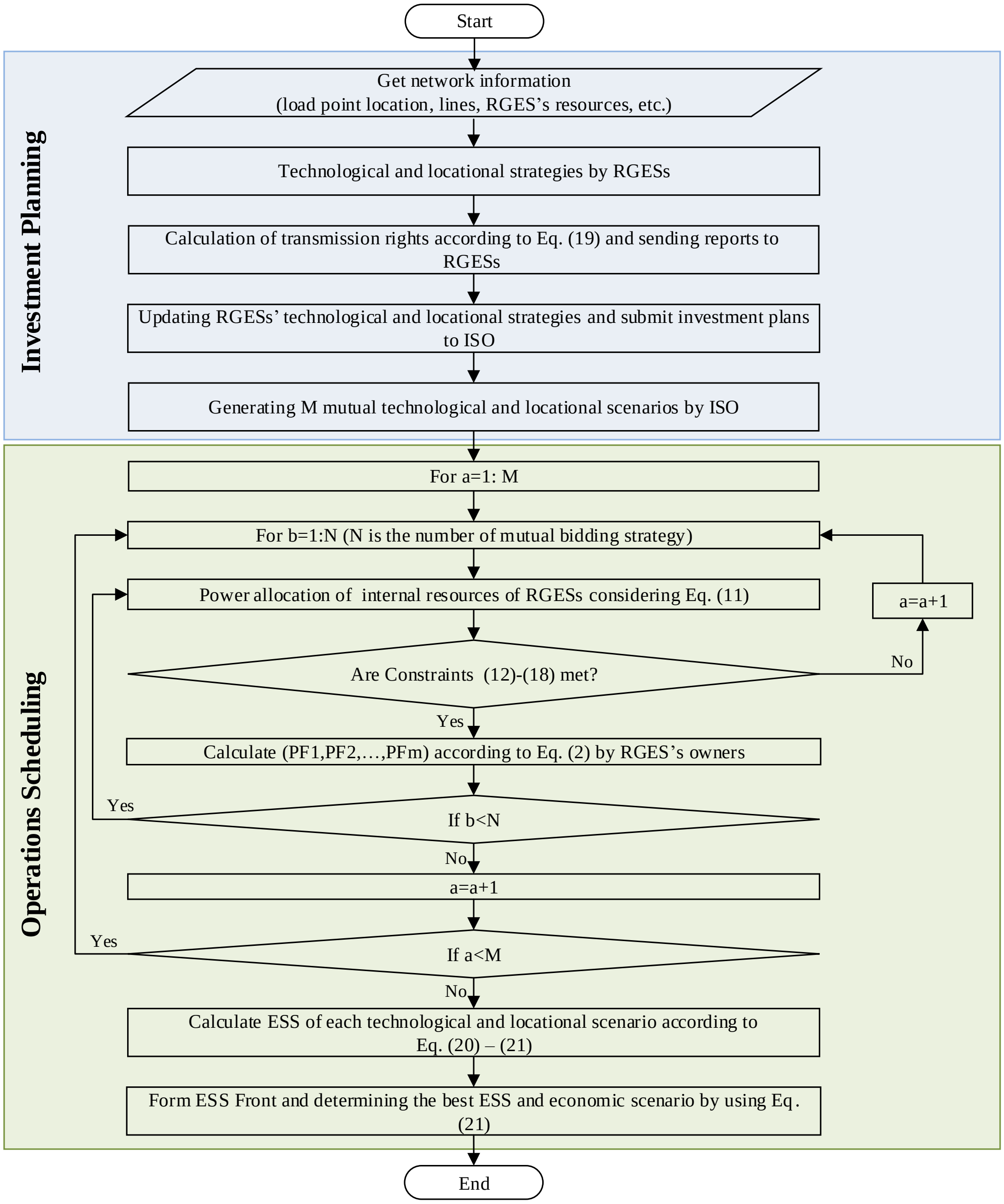

Fig. 4. Implementation steps of the proposed method

The two stages in sequence are responsible to address the “Investment Planning” and “Operations Scheduling” sub-problems, respectively. At the investment planning stage, RGESs generate different scenarios by choosing different technologies together with related sittings and capacities for their internal energy sources and send them to STEPs for transmission right costs calculations. Having had the marginal cost of internal resources and the transmission right costs in various scenarios as reported by STEP, RGESs could finalize the investment plans and submit them to the operations scheduling stage.

In the operational phase, RGESs include different bidding strategies into each investment scenario and bid-quantity packages are formed by using evolutionary game theory. Then, for each mutual bidding strategy in each scenario, using Equation (11), ISO minimizes the total cost of supplying energy and allocates the capacity of internal resources of RGESs. In fact, in this case, a single-side market is formed. Afterward, the profit function of RGESs in the relevant scenario and the related pricing strategy is calculated and stored using equation (1).

4. Numerical Results

4.1 Test System

The feasibility of the proposed game theoretic planning model is tested on a 9-bus power system with two RGESs and 7 load centers as shown in Fig. 5. The first RGES includes buses 1 to 5 while the other one spans over buses 6 to 9. The RGESs can exchange their surplus or deficit power through the buses 5 and 9 with the upstream network. However, to support local energy trades than those with the upstream network, the energy import rates from the upstream network, are set higher than the highest bid in the internal market.

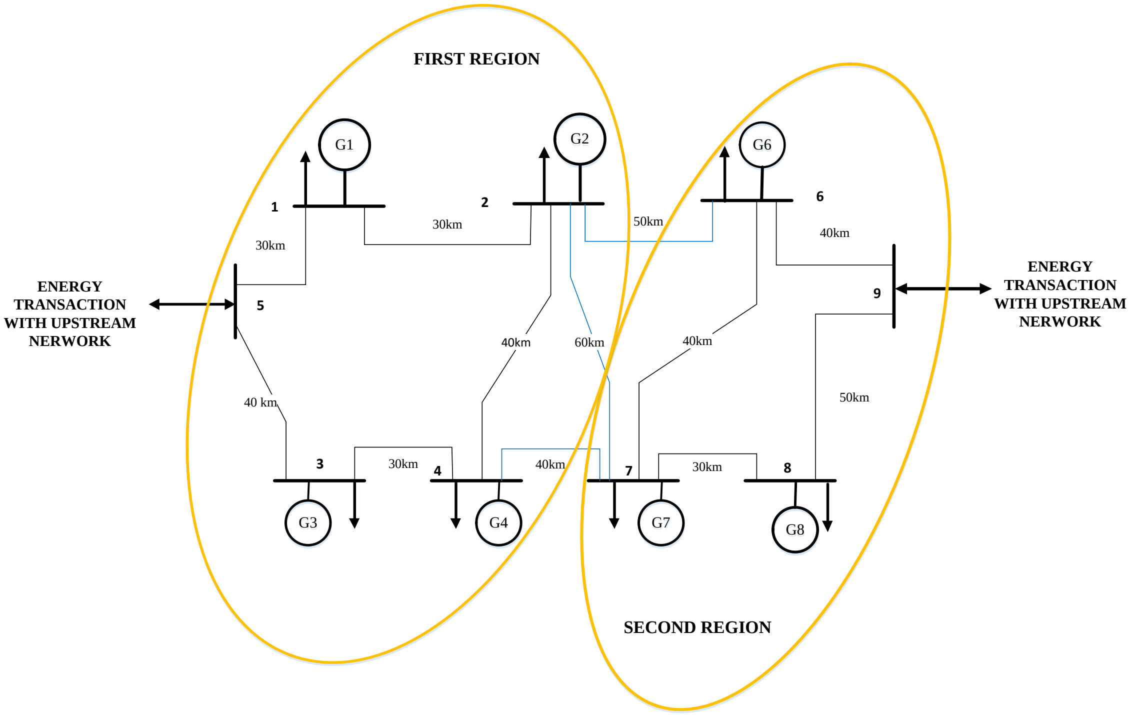

Fig. 5. Test system single line diagram

Due to geographical constraints and environmental conditions, it is possible to install hydro units in bus 1 and 6. Also, the first RGES's investor has three strategies for installing a DG unit in one of the three buss 2, 3, and 4. The other RGES's investor has two strategies for installing a DG either in bus 7 or 8. Therefore, according to Table 1, there are 6 mutual strategies for two players.

Table 1: Six mutual scenarios of players in this case study

	RGES1				RGES2		
	G1(Bus1)	G2(Bus2)	G3(Bus3)	G4(Bus4)	G6(Bus6)	G7(Bus7)	G8(Bus8)
Scenario1	*	*			*	*	
Scenario2	*	*			*		*
Scenario3	*		*		*	*	
Scenario4	*		*		*		*
Scenario5	*			*	*	*	
Scenario6	*			*	*		*

In each scenario, we will investigate 1000 mutual bidding strategies utilizing evolutionary game approach and in each bidding strategy the RGES's internal resources capacity and their profit value will be determined. The bid for each internal resource is chosen according to the actual marginal cost, the transmission right cost and the estimated local marginal price in each load point. Loads in each load level and transmission rights of each path (which are calculated utilizing contractual path method [29]) are shown in Table 2 and 3, respectively. Also, marginal cost and investment cost and other necessary data for calculating profit function of each RGES are depicted in Table 4.

Table. 2: Load demand in each load level and load point

	Load 1 [MW]	**Load 2 [MW]**	**Load 3 [MW]**	**Load 4 [MW]**	**Load 5 [MW]**	**Load 5 [MW]**	**Load 6 [MW]**
Peak Load (760 h)	30	40	30	40	40	40	30
Mid Load (4000 h)	20	30	20	30	30	30	20
Low Load (4000 h)	15	20	15	20	20	20	15

Table. 3: Transmission rights for supplying each load point by each internal resource of each RGES [calculated by STEP utilizing contractual path method]

	Load1 [$/MWh]	**Load2 [$/MWh]**	**Load3 [$/MWh]**	**Load4 [$/MWh]**	**Load6 [$/MWh]**	**Load7 [$/MWh]**	**Load8 [$/MWh]**
G1	0	3.42	5.7	8.98	10.12	10.12	15.96

G2	4.42	0	6.84	4.56	5.7	5.7	7.98
G3	5.7	6.84	0	2.28	12.54	6.84	6.84
G4	7.98	4.56	2.28	0	7.98	4.56	6.84
G6	9.12	5.7	10.26	7.98	0	3.42	5.7
G7	9.12	5.7	6.84	4.56	3.42	0	2.28
G8	11.4	7.98	9.12	6.84	5.7	2.28	0

Table. 4: Marginal cost, investment cost and other necessary data for calculating profit function of each RGES

	MC [$/MWh]	**Life Time (Year)**	**Investment Cost [$/MW]**	**Operational Cost [$/MWh]**	**Min. Power [MW]**	**Max. Power [MW]**
G1	76	20	470000	470	0	140
G2	85	20	400000	400	0	140
G3	85	20	400000	400	0	140
G4	85	20	400000	400	0	140
G6	76	20	470000	470	0	140
G7	80	20	430000	430	0	140
G8	80	20	430000	430	0	140

4.2 Results and Discussion

Various parameters such as initial investment cost, marginal cost of RGES's internal resources, Type of RGES's internal resources (fossil, hydro, wind,…), RGES's internal resources location, distribution and amount of loads and transmission rights could affect the amount of profit of RGESs. For more profit, RGES's investors try to use units with lower initial investment, marginal and maintenance costs. Also, to reduce the surcharges applied for transmission right, RGESs try to locate their units even at the border areas between the two regions so they have more chance to supply other region's loads at lower cost. Table 5 shows the results of the ESS extraction in scenarios one to six as outlined in Table 1.

Table 5. The results of ESS extraction in each scenario

	Scenario 1 (*10^9) [$] (G1,G2,G6,G7)	**Scenario 2 (*10^9) [$] (G1,G2,G6,G8)**	**Scenario 3 (*10^9) [$] (G1,G3,G6,G7)**	**Scenario 4 (*10^9) [$] (G1,G3,G6,G8)**	**Scenario 5 (*10^9[$] (G1,G4,G6,G7)**	**Scenario 6 (*10^9) [$] (G1,G4,G6,G8)**
ESS	(1.1824,1.2135)	(1.231,1.259)	(1.1180,1.234)	(1.2373,1.1152)	(1.1241,1.266)	(1.2143,1.156)

In this case study, hydro units located at bus 1 and 6 have the same cost characteristics, but the DG units used in RGES 2 have a lower marginal cost, therefore, except in scenarios 4 and 6 where the costs of transmission rights are effective, profit for RGES 2 is more than the one for RGES 1. As a result, apart from the pricing strategies, an effective factor in making more profit for RGESs is to use units with lower investment costs, and especially lower marginal cost.

Another option is to reduce the cost of the transmission right by deploying some units in the border areas between the two regions. Figure 6 shows the capacity allocation to RGESs' units in different scenarios based on minimizing the total suppling energy cost according to Eq. (11). In fact, for each of the two cross-pricing strategies in each investment scenario, the energy supply cost is minimized and the needed capacity of internal units of RGESs are determined. Then for the each bid and the corresponding allocation of the RGESs, profit function is calculated by using Eq. (2) and then for the pair of calculated profits, using the Eq. (20) and (21), ESS points of technological and locational scenario is determined.

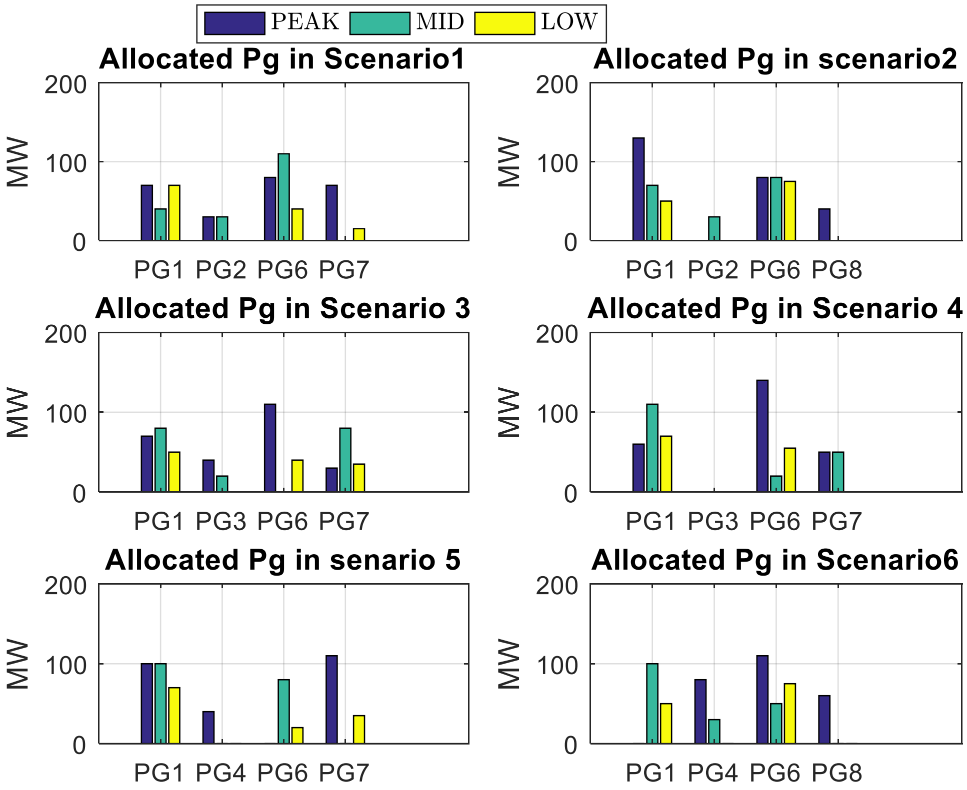

Fig6. Allocated capacity to internal resources of RGESs in each load level of each scenario

Obviously, the specific capacity of each unit is the maximum capacity assigned to one unit by ISO in capacity allocation stage, and therefore, in figure 7, the final capacity of internal resources of RGES is shown. This will always ensure that the installed capacity is greater than the total loads, which helps not only to reduce the benefits of RGESs, but also to increase the adequacy of supply. In order to prevent start-up costs, units can sell their surplus energy to the upstream network in each level and at the marginal cost of their production. Also, if the units cannot commit as scheduled, they can buy energy supplements at the highest bidder's price on the upstream network. If transmission right cost is neglected, then units with lower marginal costs will be sized in higher capacity in order to achieve greater profit. As shown in Fig. 7, units 1 and 6, which have lower marginal costs, have larger capacities. Also, DG units of the second RGES have a larger capacity due to their lower marginal cost than DG units of the first RGES. As a result of the expansion of the transmission and generation network, taking into account the RGES, it can be seen that the competition is forwarded to a direction where the use of higher-efficiency units and cheaper electrical supply to consumers is enabled.

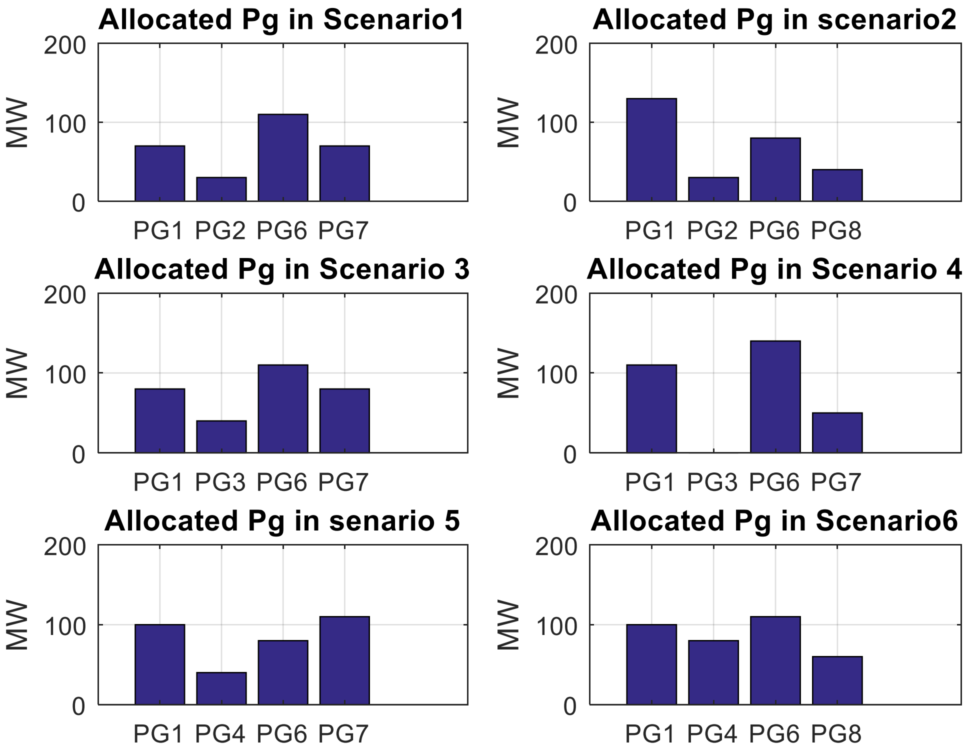

Fig. 7: Planned capacity of internal resources of each RGES in each scenario

The proposed solution method may reach only one equilibrium or multiple ESS. When multiple ESS exist, the algorithm finds a local equilibrium point. In this case study, scenario 5 is the best scenario for investors of RGESs. In scenario 5, the bidding strategy in ESS point is shown in Table 6,7 and 8 for peak, mid and low load level, respectively. It should be noted that, since numerous combinations of bidding strategies can be made, it is not possible to use conventional game theory to investigate the best mutual pricing strategy, so an evolutionary game theory is used to do this. In this regard, 1000 cross-price strategies are generated in each scenario, and equilibrium points are identified accordingly using FSM.

Table 6: Bidding strategy of RGES 1 and RGES 2 in peak load level in scenario 5

$/MWh	Load 1 (Peak-bid)	Load 2 (Peak-bid)	Load 3 (Peak-bid)	Load 4 (Peak-bid)	Load 5 (Peak-bid)	Load 6 (Peak-bid)	Load 7 (Peak-bid)
G1	88.54	95.47	86.52	99.91	89.05	96.66	94.19
G4	94.25	97.46	88.24	91.91	95.86	89.81	96.84
G6	90.12	99.53	95.07	92.20	90.35	94.01	99.18
G7	91.02	94.94	91.73	94.88	94.78	82.88	86.01

Table 7: Bidding strategy of RGES 1 and RGES 2 in mid load level in scenario 5

$/MWh	Load 1 (Mid-bid)	Load 2 (Mid-bid)	Load 3 (Mid-bid)	Load 4 (Mid-bid)	Load 5 (Mid-bid)	Load 6 (Mid-bid)	Load 7 (Mid-bid)
G1	84.18	85.71	83.41	88.31	87.73	87.71	90.07
G4	92.33	89.62	87.45	89.92	90.748	89.92	91.58
G6	85.50	84.81	86.91	88.85	85.2	87.74	81.78
G7	89.78	89.69	89.55	89.43	89.21	88.15	87.99

Table 8: Bidding strategy of RGES 1 and RGES 2 in low load level in scenario 5

$/MWh	Load 1 (Low-bid)	Load 2 (Low-bid)	Load 3 (Low-bid)	Load 4 (Low-bid)	Load 5 (Low-bid)	Load 6 (Low-bid)	Load 7 (Low-bid)
G1	81.22	82.85	84.29	84.07	85.01	85.02	91.50
G4	91.32	89.52	86.44	85	92.42	86.05	91.45
G6	85.01	83.09	86.12	84.71	82.17	84.70	83.87
G7	85.99	85.15	85.61	84.89	83.42	81.26	82.77

4.3 Decentralized decision-making

One of the benefits of the proposed method in this paper is to facilitate the decentralized decision-making process for generation and transmission expansion planning. Using the proposed approach, investors will examine the ESS points in each scenario and choose the best investment option in accordance with network and geographical constraints. Figure 8 shows the ESS points in each scenario.

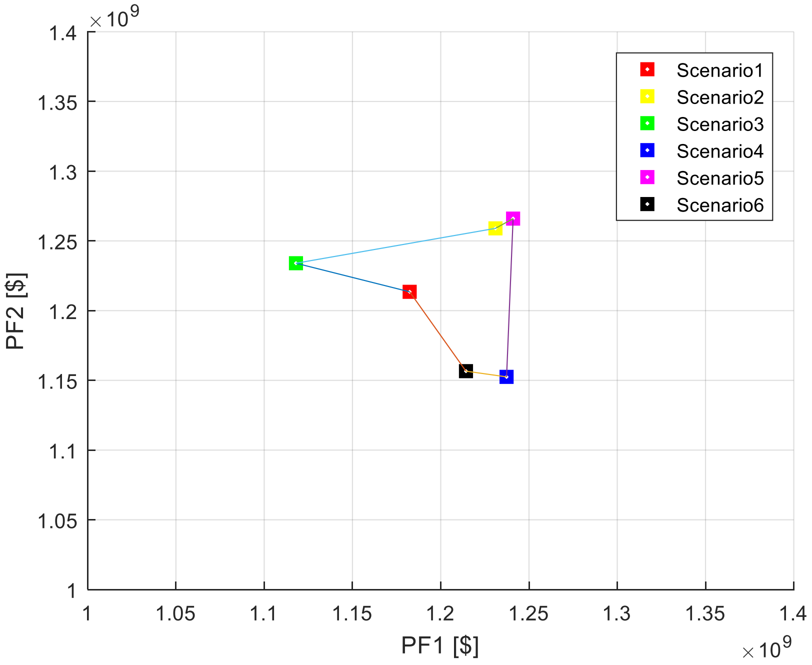

Fig. 8: ESS front for decision making

The front formed between the ESS points in different scenarios are called the ESS front. Indeed, investors are bargaining in line with various constraints, and in the area they choose the best investment scenarios. The ESS of each scenario depends on the type of internal units, installation location and biding strategy of RGESs. Therefore, in the investment planning stage the owners of RGESs are trying to select units with lower marginal cost and in order to minimize the impact of the transmission right cost establish their own units in the border regions. They can then offer more competitive prices and gain more profit.

5. Conclusion

In this paper, a new method for sub-transmission and generation expansion planning utilizing multi-RGES was presented. Expansion planning was carried out in two phases of investment planning and operations scheduling, and the ISO was considered as the only responsible for constraints check and unit commitment of internal resources of RGESs. Utilizing the game theory, different scenarios of technology and location were generated for the installation of local units of RGESs, and using evolutionary game theory in each scenario, mutual bidding strategies were analyzed accordingly. Finally, by using The FSM the ESS front of each scenario was identified.

The simulation results showed that RGESs' owners prefer to install low marginal cost units to generate more profit. They also tend to have their internal units installed near load centers to reduce the transmission right cost effect. In addition, in order to be able to meet the loads of neighboring areas, most of the investment plans offered by RGESs are those targeting the boundary points among the regions.

The extension of this work may consider effect of uncertainties such as the marginal costs of generation units, the estimated price of electricity in each load point, and the impact of the uncertainty of renewable energy units of RGESs in determination of ESS points.

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