Planning of Smart Microgrids with High Renewable Penetration Considering Electricity Market Conditions

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Abstract— **In this paper, a new method for optimal sizing of distributed generation (DG) is presented in order to minimize electricity costs in smart microgrids (MGs). This paper presents a study of the effect of wholesale electricity market on smart MGs. The study was performed for the Ekbatan residential complex which includes three smart MGs considering high penetration of renewable energy resources and a 63/20 kV substation in Tehran, Iran. The role of these smart MGs in the pool electricity market is a price maker, and a game-theoretical (GT) model is applied for their bidding strategies. The objective cost function considers different cost parameters in smart MGs, which are optimized using particle swarm optimization (PSO). The results show that applying this method is effective for economic sizing of DGs.**

Keywords—optimal sizing, PSO, renewable energy system, smart microgrid.

I. INTRODUCTION

In a smart microgrid (MG), studying the interaction between a combination of different renewable energy resources (RERs) including wind turbine (WT), photovoltaic cell (PV), fuel cell (FC) and energy storage systems (ESSs), together with the electricity market is studied, is a highly complex and challenging task. When planning electrical grids, an optimization problem is formulated where the objective function is to minimize the total cost considering system constraints. Since the RERs participate in the electricity market, their optimal size should be specified to guarantee the optimal application and operation of the MG.

Different studies have addressed the optimal sizing of RERs and ESSs. In [1], the optimal sizing of RERs has been done using genetic algorithm considering technical and economic constraints. The intermittent behavior of WT which has been modeled by vine-copula theory has been compensated in [2] by optimal sizing of ESSs. Authors in [3] have considered the optimal sizing of ESSs and RERs including WT and PV. In this study, maximizing the reliability and minimizing the cost have been realized, and firstly, the RERs have been optimally sized then the algorithm has been applied for ESSs. In [4], the optimal sizing of WT, PV, FC, Hydrogen tank and electrolyzer has been specified based on a multi-criteria method to minimize the annual cost. The optimal capacity of WT, PV and ESSs has been specified in [5], [6] and [7] to reach the minimum cost too.

The effect of RERs on electricity market and changing its structure has been studied in many sources.

In [8], the strategy has been proposed to forecast the market price based on applying WT and ESSs to maximize the profit. The dynamic programming tool has been applied in [8] to consider the intermittent behavior of WT and rapidly varying electricity market price. Authors in [9] have studied the Lithium battery operations in high penetration of RERs and presence of electric vehicles in spot and frequency regulation service markets which has been modeled in Australia electricity market.

The optimal capacity of RERs and especially ESSs considering their participant in the electricity market has been determined in some studies but it has not been studied thoroughly. In [10], the optimal capacity of ESS and PV has been determined by the global linear programming optimization algorithm, and they have participated in the electricity market. In [11], the optimal size of ESSs in electricity markets considering the uncertainties associated with rival generators' offering strategies and load level. The optimal capacity of ESSs has been studied in [12] as well. Authors in [13] have studied the influence of optimal necessary ESSs in the presence of WT by stochastic Cournot-based game and have modeled them in the South Australia market.

The contributions of the study can be listed as follows:

- Implementation of competitive market between smart MGs and distribution network and assessment of its impact on optimal sizing
- MGs' loads are increasing each year, so new units should be added to MGs for supplying this load growth. The added units at ith year will produce power during (n-i+1) years in which n shows the lifetime of the project. The optimal capacity and location of each source should be annually computed. In this paper, the different load growth in developing buses comparing to non-developing ones is considered.
- The capital cost of RERs is decreasing over the time, so one of the novelties in this study is considering the different annual forecasted capital cost in optimization problem at each year, which makes the calculations more realistic.

The rest of the paper is organized as follows. Section 2 provides the details of the Participation of smart MG in the competitive electricity market. Section 3 addresses the method for optimal sizing of smart MGs units considering smart MG as a price maker. Section 4 demonstrates the performed simulations and contains a discussion thereof. Finally, section 5 lists the conclusions that can be drawn from this work.

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II. PARTICIPATION OF SMART MG IN A COMPETITIVE ELECTRICITY MARKET

In this paper, the energy market is considered in distribution network market, and the distribution network operator (DSO) has the supervisory role in order to assess the relation between utilities in maintaining safety [14]. This relationship is shown in Figure 1.

The interaction in the electricity market is in the way that utilities propose price and power based on their capability and constraints in producing power, and the coordination between different units. These suggestions are presented to DNO, and DNO sort them from lowest price to highest price, and the market clearing price (MCP) is determined.

In this study, the GT is applied, and the smart MG can buy and sell energy to network, so it is either seller or buyer. In both cases, the smart MG is optimized to reach the minimum cost, as a result of buying and selling energy in the lowest price and highest profit is the main goals, respectively.

The main objective of each player in the market is to maximize the profit of selling/buying energy. Each generator intends to sell electricity in the highest price while each buyer intends to buy electricity in the lowest price. DNO receives buying/selling suggestions, and determines the MCP.

The price which is suggested by each company has an important role in determining their loss and profit. Different strategies and methods can be applied to determine the electricity price, and the best method is the one which reaches the utility to the lowest price.

At first, participants in the electricity market should calculate their marginal cost and announce it to DNO. DNO determines the primary MCP based on different information. DNO clears the market based on the information acquired by market players. Each generation players suggest a price based on the most expensive unit.

A. Cournot modeling

In Cournot method, after the primary suggestion of players to market and determining the primary MCP by DNO, the primary MCP is multiplied by a small coefficient, then it proposed to the participants.

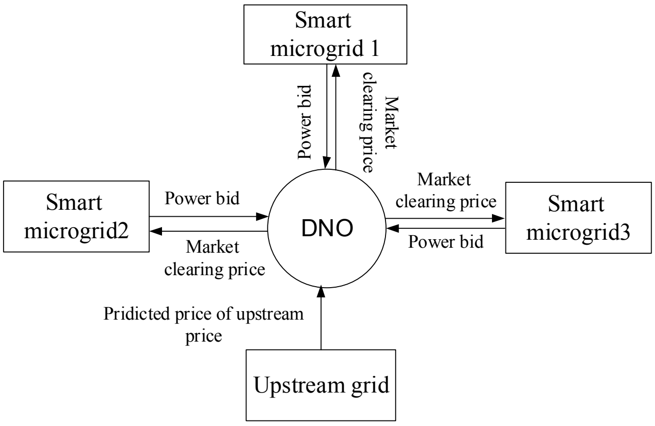

Fig 1. The interaction between different participants in the electricity market

The market players after receiving the primary cost, optimize their objective function in order to minimize the cost. In the next steps, equation 1 is used to determine the price [15].

$$MCP^{j} = MCP^{j-1} - \alpha \sum_{i=1}^{n} P_i^j \tag{1}$$

where α ($/kw2) determines the demand coefficient, which shows that increasing the power system capacity decreases the electricity price. $\sum_{i=1}^{n} P_i^j$ shows the aggregated production of all generators (kw), and j is the number of each step. This equation is stopped when MCP doesn't change.

III. MODELING OPTIMAL SIZING OF SMART MGS UNITS CONSIDERING SMART MG AS PRICE MAKER

The objective of this section is to determine the optimal size of units including the number of wind turbine, photovoltaic arrays, and the capacity of electrolyzer, Hydrogen tank, fuel cell, micro turbine, battery and AC/DC inverter in smart MGs No. 1, No. 2 and No. 3. The system cost includes the investment net present value (NPC), operation & maintenance (O&M), fuel, equipment replacement, smart devices, incentives related to participation in demand response programs, any cost related to power interruption over 20-year life cycle and buying and selling electricity cost with distribution network considering smart MGs as price maker.

The objective function is defined as follow:

$$\begin{aligned} OF_{sizing} = Min\Bigg\{ & \sum_{i}\sum_{j=1}^{N_{year}} NPC_{i.j} + \sum_{j=1}^{N_{year}} Cost_{shedd.j} \\ & + NPC_{Trans} + \sum_{n} NPC_{SA.n} \\ & + \sum_{n} NPC_{incentive.n} \\ & + \sum_{j=1}^{N_{year}} Cost_{buy.j} \\ & - \sum_{j=1}^{N_{year}} Cost_{sell.j} \Bigg\} \end{aligned} \tag{2}$$

where *i* shows the utilities in smart MG, Nyear is the project lifetime, $\sum NPC_{Trans}$ represents the net present value of the distribution transformer. $NPC_{incentive.n}$ determines the net present value of the nth smart appliances incentive.

The penalty cost for shed load can be calculated as follows:

$$Cost_{shedd} = LOEE \times C_{shedd} \tag{3}$$

$NPC_{incentive.n}$determines the net present value of the *n*th smart appliances incentive, which can be calculated as below:

$$\begin{aligned} NPC_{incentive.n} = (& Incentive\_avl_n \\ & + Incentive\_shift_n) \times PWA \end{aligned} \tag{4}$$

where $Incentive_avl_n$and $Incentive\_shift_n$ calculated by the following equations:

$$Incentive\_avl_i = \frac{1}{5}\frac{SAC_i}{N\,(start - ave)_i} \times N\,(avl)_i \tag{5}$$

$$Incentive\_shift_i = \frac{SAC_i}{N\,(start - ave)_i} \times N\,(shift)_i \tag{6}$$

where SACi is the surplus cost which should be paid for ith appliance (e.g., washing machine). $N\,(\mathrm{start} - \mathrm{ave})_i$ determines the average usage number of ith smart appliance during one year. N (avl) shows the availability number of ith appliance, and $N\,(\mathrm{shift})_i$ specifies the shifting number of ith appliance annually.

Different constraints related to angle of PV array, the amount of saved energy in tank, the operational constraints of network and the maximum production of each source is considered in this study.

IV. SIMULATION AND RESULT DISCUSSION

The Ekbatan residential complex is considered as the research case study. Ekbatan has three separate sets of buildings called respectively phase 1, 2 and 3 considered as smart microgrids. Although there is no electrical connection between them, each of these phases is connected to 63/20 kV substation by a 20 kV cable. The underground 20 kV cables are applied in distribution grid in Ekbatan complex.

The schematic of this MG is depicted in Figure 2. To reach this point, the electricity tariff in IRAN is used. The off-peak rate is equal to 0.1 $ while the peak rate is equal to 0.15 $.

The smart microgrid No.1 consists of WT, PV panel, FC, Electrolyzer, Hydrogen tank, controllable loads (washing machine, dishwasher, heating/cooling system and plug-in electric vehicles) and uncontrollable loads.

The line data for this MG is presented in Table I. The schematic of MG No. 1 and the single-line diagram of MG No.1 are represented in Figure 3 and 4.

A. The primary MCP calculation

In order to simulate electricity market, the primary MCP should be given to smart MGs which is applied in optimization and power suggestion. The price of upstream market in a sample day is presented in Table II.

In order to determine primary MCP, DNO receives all marginal cost and all players' power. Then, the marginal cost and the power related to sellers is sorted from the lowest to the highest.

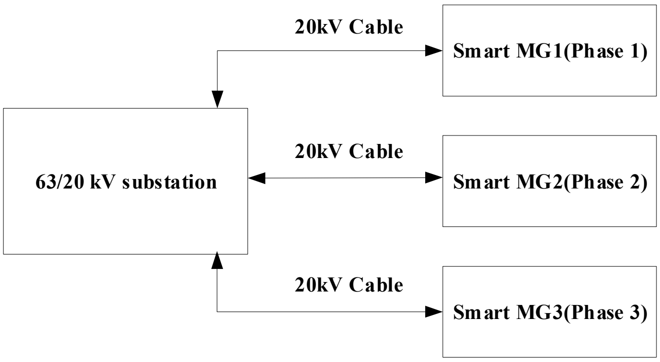

Fig 2. Schematic of MG

TABLE I: THE LINE DATA FOR SMART MG 1

First bus	Second bus	Resistance (pu)	Reactance (pu)
A1	A2	0.0058	0.0029
A2	A3	0.0308	0.0157
A2	A4	0.0102	0.0098
A4	A5	0.0939	0.0846
A5	B1	0.0255	0.0298
B1	B2	0.0442	0.0585
A3	B3	0.0282	0.0192
B3	B4	0.0560	0.0442
B4	C2	0.0559	0.0437

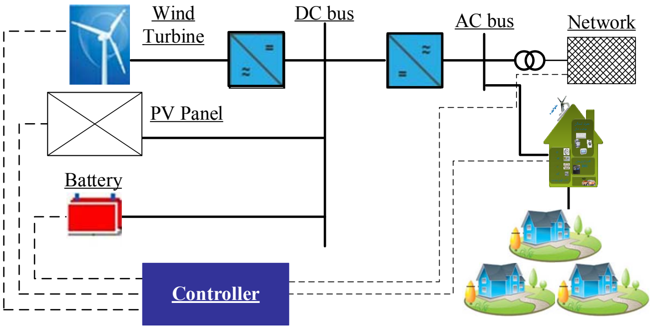

Fig 3. Schematic of MG No. 1

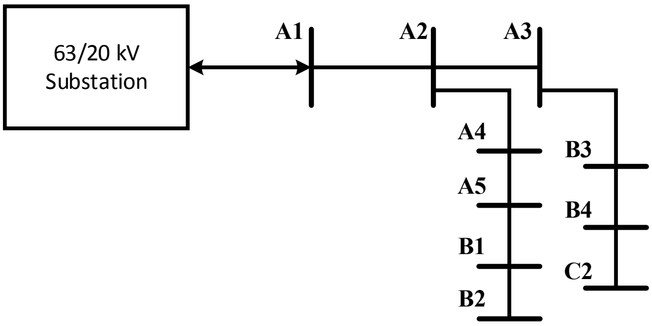

Fig 4. Single-line diagram of MG No. 1

TABLE II. THE PRICE OF DNO UPSTREAM MARKET

Time (hour)	1	2	3	4	5	6	7	8
The upstream market MCP ($/kw)	13.8	13.8	13.6	13.6	13.6	13.6	13.88	13.88
Time (hour)	9	10	11	12	13	14	15	16
The upstream market MCP ($/kw)	13.88	13.88	13.88	13.88	13.88	13.88	13.88	13.88
Time (hour)	17	18	19	20	21	22	23	24
The upstream market MCP ($/kw)	13.88	13.88	13.88	13.88	13.88	13.88	13.88	13.88

The marginal cost and power related to buyers are arranged from the highest to the lowest as well. Where these two curves touch each other is called primary MCP. This MCP is the lowest and the ideal MCP from the DNO point of view.

The amount of MCP is multiplied by a small coefficient, then it is announced to smart MGs. In this study, the coefficient is assumed 1.02. As the characteristics of different units in the market are similar together, the obtained results are close to each other which is presented in Table III. At first, participants in the electricity market should calculate their marginal cost and announce it to DNO. Market-clearing is done by DNO based on the information acquired by market players. Each generation player suggests a price based on the most expensive unit.

B. The final MCP calculation based on presented method

The participants in the market suggest their proposed power to DNO based on the primary price determined by DNO, which alters the proposed price of DNO to market players. The participants identify the best condition to propose power to DNO, this procedure continues until the Cournot equilibrium is achieved. The final price is presented in Table IV. As can be seen in Table IV, the price is low in the first hours because of the load characteristics, which are residential. The price is increasing in the morning which is low between 2 and 8 hours. The market price increases after the load growth. The smart MGs are price maker and cause changes in the distribution network price.

C. The smart MG cost in the competitive electricity market

In this section, the optimal size of DGs in smart MGs are determined which is compared to the condition that the smart MGs has no effect on the electricity market and receive the price. When MGs participate in the competitive market, the amount of sell and buy MGs with distribution network is determined according to objective function optimization and using final MCP. In this condition, the buying and selling amount is specified based on the final MCP and the MGs' demand, which is more realistic. At hours, the final MCP increases; the amount of sold power rises by MGs. On the other hand, when final MCP decreases, the amount of bought power increases from upstream network. The optimal sizes of different components in the smart MG before and after its participation in the electricity market are shown in Figure 5.

TABLE III: THE PRIMARY MCP IN EACH HOUR OF THE SAMPLE DAY

Time (hour)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
The upstream market MCP ($/kw)	13.89	13.89	13.08	13.08	13.89	13.11	13.99	13.89
Time (hour)	9	10	11	12	13	14	15	16
The upstream market MCP ($/kw)	13.90	13.90	13.91	13.90	13.90	13.90	13.90	13.90
Time (hour)	17	18	19	20	21	22	23	24
The upstream market MCP ($/kw)	13.89	13.90	13.90	13.90	13.90	13.90	13.90	13.90

TABLE IV: THE FINAL MCP IN EACH HOUR OF THE SAMPLE DAY

Time (hour)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
The upstream market MCP ($/kw)	13.60	13.21	13.03	12.89	13.18	13.10	13.22	13.29
Time (hour)	9	10	11	12	13	14	15	16
The upstream market MCP ($/kw)	13.76	13.67	13.65	13.56	13.50	13.57	13.59	13.64
Time (hour)	17	18	19	20	21	22	23	24
The upstream market MCP ($/kw)	13.46	13.72	13.65	13.72	13.38	13.29	13.87	13.44

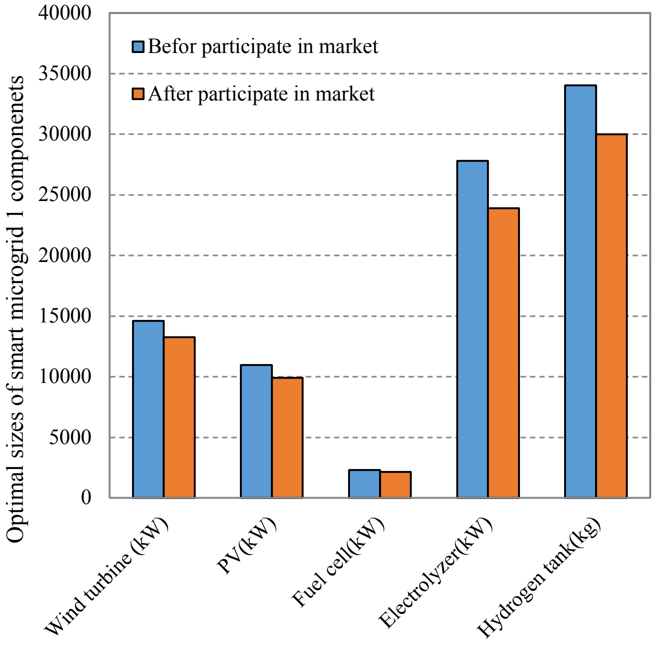

Fig 5. Optimal sizes of smart MG No. 1 components before and after participation in market

V. CONCLUSION

The main aim of this paper was to analyze the optimal sizing of a smart MG, specifically one with a high penetration of RERs. The effect of controllable residential loads and the participation of MG in the electricity market as price maker was analyzed. In this paper, the total cost and optimal size results are compared before and after participation in the market. When the MG and market interact with each other, the optimization using final MCP determines the amount of selling/buying from/to the MG. In this situation, when final MCP increases, the amount of sell by MGs grows. The comparison between the cost of MGs before and after participation in the market shows the reduction about 3.58%, which is related to a logical transaction between MG and the electricity market, so the amount of sold electricity increases when the final MCP is high, and if the MCP is low, more power should be bought.

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