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REGULAR PAPER

A Novel Demand Response Method for Smart Microgrids Related to the Uncertainties of Renewable Energy Resources and Energy Price

This paper presents novel methods for Demand Response (DR) programs by considering welfare state of consumers, to deal with the operational uncertainties, such as wind energy and energy price, within the framework of a smart microgrid. In this regard, total loads of microgrid are classified into two groups and each one is represented by a typical load. First group is energy storage capability represents by heater loads and second is curtailment capability loads represents by lighting loads. Next by the proposed DR methods, consumed energy of the all loads is coupled to the wind energy rate and energy price. Finally these methods are applied in the operation of a smart microgrid, consists of dispatchable supplier (microturbine), non-dispatchable supplier (wind turbine), energy storage system and loads with the capability of energy exchanging with upstream distribution network. In order to consider uncertainties, Monte Carlo simulation method is used, which various scenarios are generated and applied in the operation of microgrid. In the end, the simulation results on a typical microgrid show that implementing proposed DR methods contributes to increasing total operational profit of smart microgrid and also decreasing the risk of low profit too.

Keywords: Demand response, Smart microgrids, Operational uncertainties, Monte Carlo simulation, Renewable energies

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1. NOMENCLATURE

P_{grid} : Exchanged power with upstream distribution network (kW)
P_{grid}^{max} : Maximum capable of exchanging energy with upstream distribution network (kW)
P_{wt} : Produced energy of wind turbine (kW)
$P_{wt, avg}$: Predicted average wind turbine generation for next 24 hours (kW)
P_r : Wind turbine rated generation capacity (kW)
P_{mt} : Produced energy of microturbine (kW)
P_{bat} : Exchanged power with energy storage system (kW)
P_{nc} : Demand power of uncontrollable loads (kW)
P_{heater} : Demand power of heating loads (kW)
P_{light} : Demand power of lighting loads (kW)
ρ_{grid} : Energy price of upstream distribution network ($/kWh)
$\rho_{grid, avg}$: Predicted average energy price of upstream distribution network for the next 24 hours (S/kWh)
ρ_{nc} : Price of selling energy to uncontrollable loads ($/kWh)
ρ_{heater} : Price of selling energy to heater loads ($/kWh)
ρ_{light} : Price of selling energy to lighting loads ($/kWh)
C_{mt} : Operation cost of microturbines
C_{wt} : Operation cost of wind turbines
C_{bat} : Operation cost of energy storage system
V : Wind speed (m/s)
V_{ci} : Cut-in wind speed (m/s)
V_{co} : Cut-out wind speed (m/s)
V_r : Rated speed of wind turbine (m/s)
T_{actual} : Actual temperature of house (^{oC})
$T_{desired}$: Desired temperature of residents (^{oC})
T_{max} : Maximum tolerable Temperature by residents (^{oC})

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T_{min}	:	Minimum tolerable Temperature by residents (^{oC})
T_{in}	:	Inside temperature of house (^{oC})
T_{out}	:	Outside temperature (^{oC})
H_{wall}	:	Rate of heat flow
K	:	Thermal conductivity (w/m.K)
COP	:	Coefficient of performance
ρ_{air}	:	Air density (Kg/m^3)
V_{room}	:	Room volume (m^3)
C_{air}	:	Specific heat capacity
A	:	Wall area (m^2)
L	:	Wall thickness (m)
E	:	Illumination flux of lighting loads (Lux)
$E_{suggest}$	:	Suggested illuminance for the desired place (Lux)
E_{min}	:	Minimum illuminance for the desired place (Lux)
E_{Lamp}	:	Produced illuminance of lamp (Lux)
E_{day}	:	Daylight illuminance (Lux)
φ	:	Total produced luminous flux of lamps
φ'	:	Luminance flux of lamp reaches to the desired surface
Cu	:	Coefficient of utilization for lamps
LLF	:	Light loss factor
l	:	Length of desired place (m)
w	:	Width of desired place (m)
η	:	Light utilization coefficient of lamp
n	:	Number of busbars
x	:	Number of microturbines
V_i	:	Voltage of busbar i
$P_{L\,i\text{-}j}$	:	Exchanged power between two busbars of i and j (kW)
$P_{L\,i,j}^{max}$	:	Maximum capability of exchanging power for power line that situated between two busbars of i and j (kW)

2. INTRODUCTION

Nowadays energy has become a fundamental issue in the process of developing countries. In fact, energy resources play an important role in developing and self sufficiency of countries. Therefore recognition and optimal operation of the energy resources have a great importance. During the recent years, using renewable energy resources such as wind and solar energies is significantly being considered by various countries. This fact follows from high price, negative impacts on environment and finite feature of fossil fuels; hence, many energy providers motivate to use renewable energy resources. However, these resources have the problems of stability and availability. In order to solve these problems some solutions were proposed which one of them is distrusted generation (DG) by these resources. Nevertheless, increasing the number of DGs contributes to another problem about their management. Having solved this problem by power engineers results in introducing smart grid structure which would consists many smart microgrids. Furthermore, by implementing these structures, another important application emerges which is known as demand response technology (DR). This technology is defined as the changes in electric usage by end-use customers from their normal consumption patterns, in response to changes in price and encouragement payment [1]. Also this technology could be used as a solution to deal with the uncertainty of the renewable energies. Implementing DR programs needs fast communicational lines and smart infrastructures, which smart microgrids could fulfill these requirements.

Microgrids are low voltage intelligent distribution networks which consist of various distributed generators, storage devices and loads. They can be operated as connected or disconnected (island mode) from upstream distribution network (UDN). In order to operate microgrids, some controlling strategies have been proposed, which one of the most important ones is central control method. In this method, microgrid operation responsibility is in the charge of a microgrid manager or smart energy management system (SEMS). Moreover optimal operational planning of microgrids is a controversial issue which is a nonlinear optimization problem with many continues variables. This problem is defined as minimization costs or maximization profit from the operator point of view. Some of the most important methods for solving this problem are heuristics-based method using Priority List (PL) [2], [3], dynamic programming [4], [5], Lagrangian relaxation [6], [7], [8], branch and bound [9], genetic algorithm [7], partial swarm optimization (PSO)[10].

Although, many papers were published in the operational field of microgrids, a few number of them considered uncertain factors. For instance, paper [11] presents a developed energy management system for a microgrid which a probabilistic occurrence limit has been considered for wind power but only predicted values have been used for other probabilistic factors. Also, multiobjective function has been used for operational planning of a microgrid in papers [12], [13], [14],[15]. This multiobjective function consists of a part for minimization costs and another part for minimization emissions due to DGs but they do not consider uncertain factors. Paper [16] proposed a smart energy management system for microgrids which consist of power forecasting module, energy storage system management module, and optimization module. In this paper decision variables have been simplified into a single-objective optimization problem then genetic algorithm has been used for solving this problem. As mentioned, most of the papers in the field of the microgrids, did not consider uncertainties, and only they used predicted values of probabilistic factors for operational planning. In order to solve this problem, proposed methods in the field of power systems operation by considering uncertainties should be generalized to microgrids. Some of these methods consists chance constraint programming method[17], multiobjective PSO[18], and Monte Carlo simulation method[19], [20]. Monte Carlo method has many advantages such as simultaneous consideration of many probabilistic factors, not adding extra constraint to OF, not excessive complexity, and easy to implementation; therefore, it has been applied in this paper based on[19].

As described before, DR could consider as a solutions to deal with the uncertainties. These programs are not only applied for large consumers but also domestic consumers could be involved in them. For example there are large potential for virtual energy storage (e.g. in inert thermal processes for refrigerator, and air-conditioning), which can help to maintain the energy balance in the controlled area [21]. In this regard, paper [22] described that shifting demand of air-conditioning (AC) systems from peak to off-peak hours contributes to reducing market clearing price; hence, its benefits would be realized not only by the DR programs owners but also by all purchasers in the electricity market. Paper [23] proposed a direct load control method for AC systems and claimed that, increasing room temperature results in reducing consumption of these loads in some periods such as peak times. Then this reduced energy could be bid for the electricity market. The structure of this method is like virtual power plant that AC systems might be located in the different places so they could be aggregated. Paper [24] presents demand response for AC systems through active controllers and market price signals. Moreover, consumption of the some loads such as lighting loads could be reduced according to the generation rate of renewable resources or energy price. In addition, in paper [25] three DR strategies consist of demand saving, demand shifting, and peak time generation have been proposed which Lighting loads were located in the demand saving group. For these loads five methods consist of zone switching, luminaire switching, daylight, stepped continues dimming, and turn off outdoor lights have been presented. Then zone switching method was used for controlling lighting loads, which suggested turning off lights of unoccupied zones or zones where daylight is enough. Ref [26] proposes a model of the electricity market that captures the uncertainties on together the operator and user sides. The system operator implements a chronological linear pricing plan that depends on real time demand and renewable generation in the measured time combining real time pricing with time of use pricing. In Ref [27], a confidentiality preserving method for incentive based demand response programs in the smart grid is proposed, that enables the demand response supplier to calculate personality demand curtailments and demand response rewards while preserving customer privacy. Ref [28] presents a system extensive demand response management form to organize demand response supplied by residential customers. The objective of the model is to flatten the entire load shape that is subject to minimum individual price of customers. Ref [29] investigates a novel dispersed control algorithm by randomizing smart appliances' responses to explain the frequency fluctuation problem. Ref [30] proposes a two stage model for the energy pricing and dispatch problem faced by a smart grid retailer who plays the role of a mediator agent between a wholesale energy market and end consumers. Ref [31] describes a real time price based demand response method for achieving optimal load control of equipments in a facility by forming a virtual electricity trading procedure. Ref [32] provides a complete assessment of different demand response methods and programs, based on the motivations offered to the consumers to contribute in the program. Ref [33] studies demand response organization what time a wind farm is connected to a smart grid. Ref [34] comprehensively explores the four main aspects programs, issues, approaches, and upcoming extensions of demand response. Ref [35] proposes a innovative model of demand response management for the future smart grid that integrates plug-in electric vehicles and renewable energy resources. Ref [36] addresses the interface between several utility companies and several customers in smart grid by modeling the demand response problem as two noncooperative games: the supplier and customer side games.

In the present paper, a novel method for demand response technologies within the infrastructure of a smart microgrid to deal with the uncertainties of the wind power and energy price of UDN, has been proposed. In this regard, it has suggested classifying loads of the microgrid into two groups with energy storage capability, and curtailment capability. Next, for each group a new DR program in order to deal with the uncertainties of wind power and energy price of UDN has been proposed which is the main contribution of this paper. Finally these methods have been applied in the operation of a microgrid. Moreover, in order to operate this microgrid by considering uncertainties, Monte Carlo simulation method has been used.

In next section the proposed microgrid structure and its interactions are presented. Then in section IV, the economical models for each components of the microgrid, including generators, energy storage system, and loads are presented. Also, in this section, new DR methods for heating loads and lighting loads are proposed. In section V, the procedure of applying uncertainties in the operation of the smart microgrid by Monte Carlo simulation method is described. Then, operational model of the smart microgrid by considering uncertainties is formulated. In order to validate the proposed models, in section VI, numerical examples for a typical microgrid are employed. Moreover, the conclusions are presented at the end of the paper.

3. PROPOSED MICROGRID

A microgrid is an integrated energy network, consisting energy resources, storage systems and multiple electrical loads, operating in a single autonomous grid. Also, it can be operated either in parallel or island mode form the existing power grid. In fact microgrids are one of the main facilities to accelerate smart grid vision achievement. In addition, microgrids reduce energy bill for their consumers and result profession and income for their investors.

Like power grids, microgrids require daily operational planning, that fulfilling this task is in the charge of microgrid manager or Smart Energy Management System (SEMS) and its ownership is as cooperative in this paper. Fig. 1 shows the structure of the proposed smart microgrid, which consists of microturbine represents dispatchable resources, wind turbine represents non-dispatchable resources, energy storage system, and controllable and uncontrollable loads. Also, this smart microgrid has the capability of exchanging energy with the upstream distribution network (UDN). Furthermore, all generating units and storage systems belong to the microgrid manager. For operating of this microgrid, SEMS needs swift communication networks in order to monitor and control various parts of this microgrid. These communication networks have been shown by dashed lines in Fig 1.

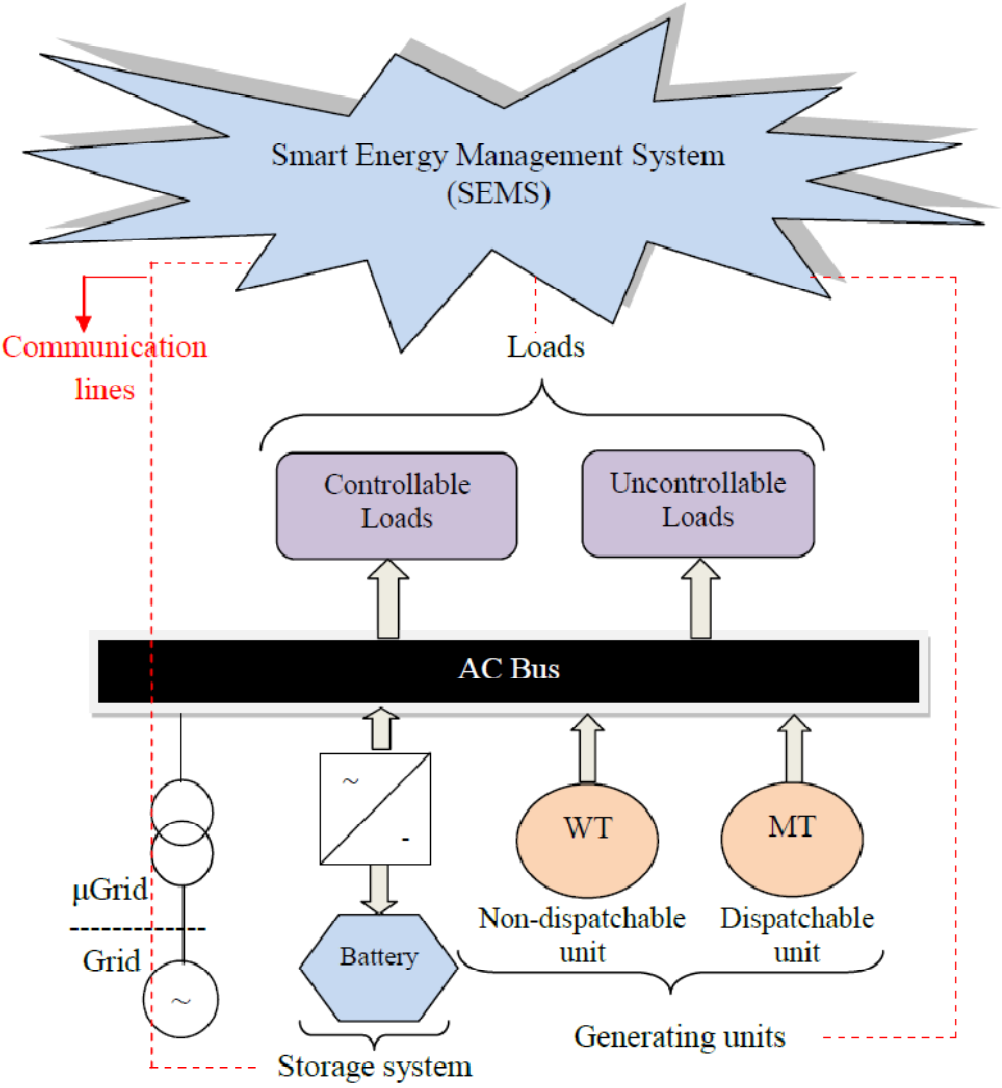

Fig. 1 : General overall structure of proposed microgrid

In order to optimal operation of the microgrid, SEMS has to deal with the following tasks:

1. Predicting generation rate of the non-dispatchable units and determine and control generating rate of the dispatchable units.
2. Deciding about the amount of the exchanged energy with UDN, which the main influenced factor in this case is energy price of UDN.
3. Deciding about the amount of the exchanging energy with ESS. In fact ESS is one of the important gadgets to foil the operational uncertainties.
4. Supplying both controllable and uncontrollable loads and of course managing

controllable loads. Controllable demands are one of the novel technologies to deal with the operational uncertainties.

4. SMART MICROGRID MODELING

In this section, each microgrid's components consist of generating units, ESS, and loads have been modeled. Also, new proposed demand response programs have been proposed for controllable loads.

3.1. Generators

3.1.1. Wind Turbine (WT)

Wind power is the conversion of wind energy into electrical energy by wind turbines, which is renewable, widely distributed, clean and with no greenhouse gases emission. The produced energy of wind turbine (P_{wt}) is related directly to wind speed and is calculated by wind turbine power curve, which is formulated as (1). In this equation A, B and C are constant coefficients which have been calculated in [37].

$$P_{wt} = \begin{cases} 0 & 0 \leq V < V_{ci} \\ P_r \times (A + B.V + C.V^2) & V_{ci} \leq V < V_r \\ P_r & V_r \leq V < V_{co} \\ 0 & V_{co} \leq V \end{cases} \tag{1}$$

In this paper, in order to involve wind turbine generation cost in the operational model, a constant cost, consists of operation and maintenance cost and capital cost has been considered for it.

3.1.2. Microturbine (MT)

Microturbines are the new generation of the combustion turbines which are used for constant electrical energy generation. The size of these generators is small and they could be installed at the side of the consumers. These generators have several advantages such as low maintenance cost, high lifetime, small dimensions, low weight, high efficiency, low emissions, and fast start-up.

In order to model these generators in the operation program, a cost function consists of fuel cost, operation and maintenance cost, start-up cost and emissions cost have been considered which presented in [19]. Also, operational constraints including maximum and minimum generation capability and rate of increasing or decreasing power have been considered in this modelling.

3.2. Energy storage systems (ESS)

Nowadays energy storage systems have been widely considered in the power systems. These technologies are applied to balancing dynamic sources and loads, coping with the intermittency of renewable energy resources and facilitating the integration of them, managing peak demands and of course enabling secure microgrids. In fact, ESS can be used as a reserve unit in microgrids and supplies loads in critical times even technically or economically. On the other hand by smart grid infrastructures for ESSs such as V2G (electrical vehicle to grid), consumers can store energy when it is cheap and sell it back to the grid when it is expensive.

Batteries are the principal technology and play a key role in the field of energy storing, which have been used in the typical microgrid of this paper too. In order to involve their utilization cost in the operational model, a constant cost consists of operation and maintenance, has been considered for them.

3.3. Loads

In this section new proposed demand response (DR) programs have been presented. Generally, this microgrid has two types of loads, including controllable and uncontrollable loads. Therefore, microgrid manager should supply these loads and get energy cost from them in according to their types. These loads might be joined to this microgrid for economical or reliable reasons.

3.3.1. Uncontrollable loads

A part of the loads of this microgrid is uncontrollable loads which there are not any type of DR programs implemented on them; therefore, their demand (P_{nc}) must be met at any time or situation. Because of the high reliability level, selling price of energy to them is considered 20% more than the energy price of UDN.

3.3.2. Controllable loads

Smart microgrid technology provides an appropriate infrastructure for DR programs at the domestic loads side. Generally, domestic loads from the aspect of DR technologies could be divided into three groups as described below.

First group of loads has the capability of energy storing. Some of these loads have batteries such as electrical vehicle, so the electrical energy is easily stored and then could be discharged and utilized whenever it is necessary but others have the capability of virtual energy storing (e.g. in inert thermal processes for refrigerators, air conditioning and electrical heaters). In fact, these loads convert electrical energy to some other form of energy such as thermal, chemical or mechanical and then store it (e.g. in a thermally isolated mass). In this way which is known as so called virtual demand side storing energy, energy cannot have feedback to the grid but it can be stored and used by the end-user process; as a result, energy consumption time becomes more flexible. Also, in this strategy the welfare level of consumers should be considered.

Second group of loads such as lighting loads has the capability of curtailment. These loads demand must be supplied at the requested time and it cannot be shifted to the other times; however, it can be adjusted according to the operational strategies and of course welfare level of the consumers.

In this microgrid, consumers have their loads joined to these DR programs in order to reduce their electrical bill. Therefore, microgrid manager must rebate their energy cost to satisfy them and; on the other hand, he could increase his profit by the appropriate DR strategies.

To sum up, two highly effective factors in the profit of this microgrid are generation rate of the wind turbine and energy price of UDN. In fact, uncertainty is the main inherent feature of these factors which make the optimal operation of the microgrid so difficult. Subsequently, proposed DR programs of this paper attempt to deal with these uncertainties by making demand of the loads couple with these uncertain factors and; consequently, increase total profit of microgrid. The mentioned DR programs for each group of loads have been described in follo

3.3.2.1. First Group (Energy storage capability)

As it was described, this type of loads has the capability of storing energy whether by battery or in the virtual way. In this paper electrical heating loads represent this group and have been modeled in the operational planning. According to this strategy microgrid manager could directly control these loads in order to increase his profit; however, welfare level of consumers must be considered and their energy cost should be rebated.

Electrical heating loads are one of the major consumers of the electrical energy so controlling these loads by considering their virtual energy storage potential in a proper way contributes to achieving more profit in the microgrid operation. These loads usually have thermostat and temperature controller, which could be controlled according to the desired temperature of the residents; because of this, by controlling room temperature, their demand could be controlled.

In the proposed DR method, adjusted temperatures of these loads have been related to the generation rate of wind turbine and energy price of UDN. Thus, if the generation rate of the wind turbines is high and the energy price of UDN is low, then the temperature of these loads are adjusted more than the desired temperature; therefore, the electrical energy is stored as the thermal energy which could be used at the subsequent time intervals. If it is vice versa, the temperature is adjusted lower than the desired temperature and; consequently, their consumptions are reduced. However, this temperature interval must be limited by the welfare level of the consumers.

In this method, sets of thermostats and controllers which are known as active controllers should be connected to the home energy management system and subsequently SEMS. According to this method, first consumers should determine a temperature as a desired temperature. Then SEMS calculates a temperature as an actual temperature by the proposed DR method with considering T_{max} and T_{min} ; next, apply it to loads by active controllers. Actual temperature and its constraint are shown by (2) and (3) respectively.

$$T_{actual} = T_{desired} + \Delta T \tag{2}$$

$$T_{min} \leq T_{actual} \leq T_{max} \tag{3}$$

- Determining actual temperature:

In order to determine T_{actual}, it is just enough to calculate ΔT which is related to the generation rate of the wind turbine and energy price of UDN. In this regard, norms of the wind generation ($\sigma_{P_{wt}}$) and energy price of UDN ($\sigma_{\rho_{grid}}$) are calculated as follow:

$$\sigma_{P_{wt}} = \frac{P_{wt} - P_{wt,avg}}{P_{wt}} \tag{4}$$

$$\sigma_{\rho_{grid}} = \frac{\rho_{grid} - \rho_{grid,avg}}{\rho_{grid}} \tag{5}$$

Then, because the energy price has contrary effect in this method, so these two norms form σ as follow:

$$\sigma = \sigma_{P_{wt}} - \sigma_{\rho_{grid}} \tag{6}$$

In fact, σ is a criterion to apply the variation effects of the wind turbine generation and the energy price of UDN at the interior temperature and consequently consumption of the heating loads. This factor is related to the interior temperature of homes (T) according to the Fig 2. In this figure R_{high} and R_{low} are slopes of diagram, which are calculated by (7) and (8) respectively.

$$R_{high} = \frac{\sigma_{max}}{T_{max} - T_{desired}} \tag{7}$$

$$R_{low} = \frac{-\sigma_{min}}{T_{desired} - T_{min}} \tag{8}$$

Also, according to the Fig 2. ΔT is calculated as follow:

$$\Delta T = \begin{cases} \dfrac{\sigma}{R_{high}}, & \sigma > 0 \\ \dfrac{\sigma}{R_{low}}, & \sigma < 0 \end{cases} \tag{9}$$

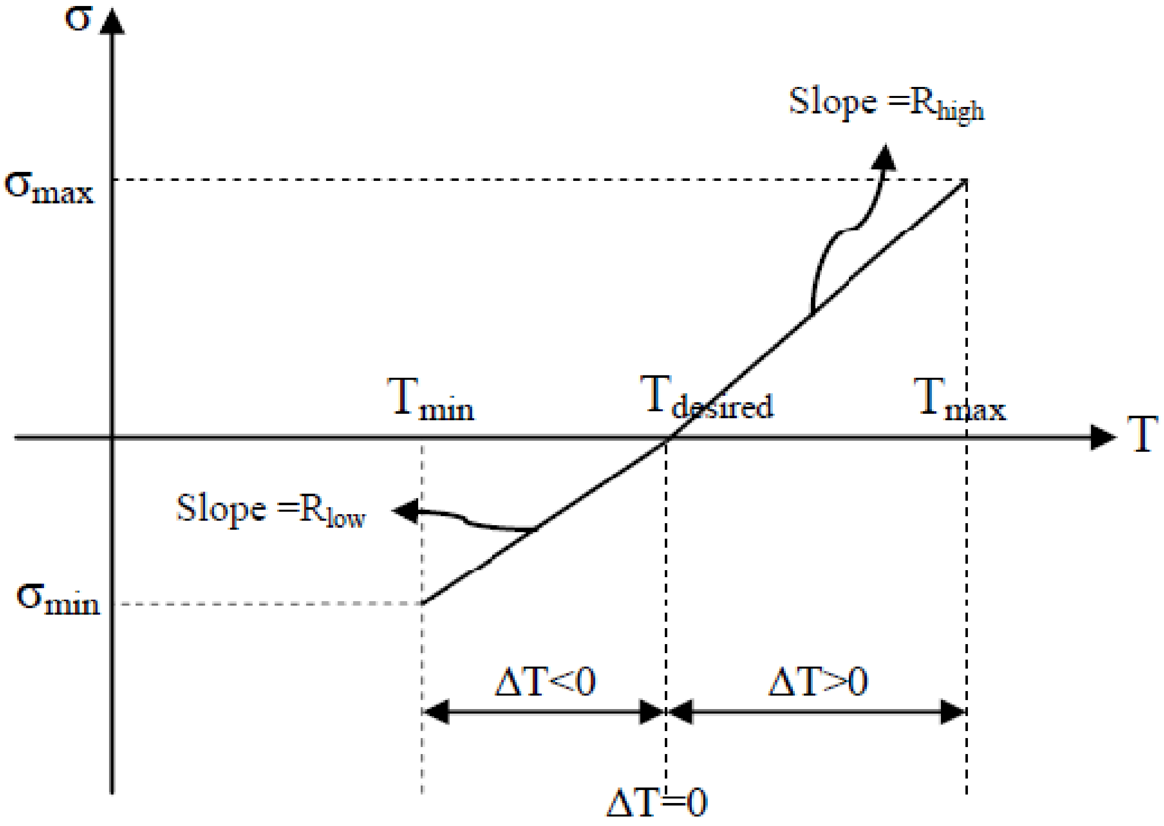

Fig. 2 : Graph of proposed demand response program for electrical heating loads

Then, by considering (2) and (9), actual temperatures of the homes are calculated as follow:

$$T_{actual} = \begin{cases} T_{desired} + \dfrac{\sigma}{R_{high}}, & \sigma > 0 \\ T_{desired} + \dfrac{\sigma}{R_{low}}, & \sigma < 0 \end{cases} \tag{10}$$

- ❖ Determining consumed power of the heating loads with regard to T_{actual} and T_{out}:

In order to achieve actual temperature of (10), consumed power of the heating loads should be provided. In paper [38] this process was calculated for air-conditioning systems which is extended to these loads as follow. In fact, heating loads must cause temperature difference according to (11) at any time interval.

$$\Delta T_i' = T_{actual_i} - T_{actual_{i-1}} \tag{11}$$

In order to cause this temperature difference, required power of the heating loads at time interval i could be obtained as follow:

$$P_{heater,i} \times COP \times 1 - H_{wall} \times t = \rho_{air} \times V_{room} \times C_{air} \times \Delta T_i' \tag{12}$$

This equation is one of the basic equations of the thermodynamic. In this equation t stands for time intervals which is one hour for this modeling, COP is coefficient of the performance which is defined by ratio of the transferred heating energy to space per hour to the electrical energy consumption of the system which is usually one for domestic heaters. Moreover, H is the rate of the heat flow and calculated as (13). For simplicity, rate of heat flow has been calculated separately for $T_{actual,\ i-1}$ and $T_{actual,\ i}$, then by averaging these two values, H_i is obtained as follow:

$$H = KA\frac{T_{out} - T_{in}}{L} \tag{13}$$

Finally, selling price of energy to these loads is considered 10% lower than the predicted mean energy price of UDN. Moreover, other similar domestic loads such as refrigerators, water heaters and air-conditionings could be modeled according to the proposed method.

3.3.2.2. *Second group (curtailment capability)*

SEMS can curtail demand of these loads according to the operational strategies (technical or economical) and of course by considering welfare level of the consumers. In this paper, lighting loads represent this group. These loads are one of the high consumption loads especially at the early night which result in peak demand.

In the proposed method of DR program for these loads, the illumination level of the lighting loads and consequently the consumption of them are coupled and adjusted with the generation level of the wind turbine and energy price of UDN. In order to apply this proposed method, smart home infrastructures especially smart controllers for lighting loads which each of them consists of an illumination sensor and a controller are required. In the proposed procedure, first illumination level for each section of the home according to the proposed method is calculated. This level must be located between the minimum and suggested illumination level of the place. Then, these amounts are sent to the appropriate smart controller of each lighting loads. Finally, by considering illumination level of the desired place which is measured by illumination sensor, smart controller somehow adjusts lights that total illumination of daylight and lights are equal to the calculated illumination level of that place. In order to regulate lighting loads by the calculated illumination level, electrical ballast could be used. Also, because sensitivity of human eyes characteristic to the light variations is logarithmic so by logarithmic changing of lights, residents would have better feelings

- Calculating illumination level of the lights by the proposed method:

In the lighting calculations, illumination quantity is used which is defined by proportion of the luminous flux to the desired surface ratio. Also, lighting references usually propose minimum and suggested illumination level for various places, such as living rooms, bedrooms, corridors, pavements and etc. In the proposed method, illuminations of the lights are changed in the mentioned interval according to the variation of the wind turbine generation and energy price of UDN.

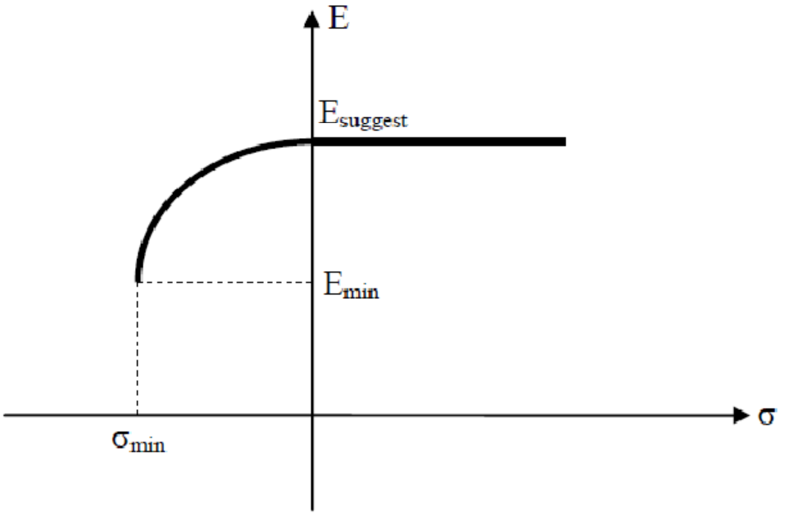

Fig. 3 : Schematically demonstration of proposed controlling method for lighting loads

In order to cause coupling between illumination levels of the lighting loads and on the other hand wind turbine generation and energy price of UDN, the normalized amount (σ) of these two factors according to (6) has been used too. Fig. 3 shows the relation between this normalized factor and illumination level of the lighting loads. According to this figure when σ is positive or zero, the illumination level of the loads are adjusted at the suggested illumination level, but when the σ is negative, this relation is depicted by a parabola curve with downward concavity. More welfare of consumers is the reason for using parabola function so that illumination variations are small in low prices deviations and vice versa.

By considering two points of Fig. 3, (0 , $E_{suggest}$) and (σ_{min} , E_{min}), and the fact that the slope of tangent line in (0 , $E_{suggest}$) is zero, equation of Fig. 3 is calculated as follow:

$$E = \begin{cases} E_{suggest}, & \sigma \geq 0 \\ -\dfrac{E_{suggest} - E_{min}}{\sigma_{min}^{2}} \sigma^{2} + E_{suggest}, & \sigma < 0 \end{cases} \tag{14}$$

where E is illuminance flux (Lux), and E_{min} and $E_{suggest}$ are minimum and suggested illuminance for the desired place respectively.

- Estimating consumption power of the lighting loads to obtain calculated illumination level of them:

In this section, lighting loads consumption has been estimated in order to achieve desired illumination level. Because total produced illumination of lights does not reach to the desired surface; therefore, coefficient of utilization is defined as (15). Also, φ is defined as (16).

$$Cu = \frac{\varphi'}{\varphi} \tag{15}$$

$$\varphi = \frac{E_{lamp}.\, l.\, w}{Cu.\, LLF} \tag{16}$$

In these equations. Cu and LLF are extracted from the lighting references, depend on type of lamps, chandeliers, and places [39]. In order to achieve illumination level of (14), estimated consumed power of the lighting loads with regard to (16) is calculated as follow:

$$P_{light} = \begin{cases} \left(E_{suggest} - E_{day}\right) \times \frac{L.w}{Cu.LLF.\eta} & \sigma \geq 0 \\ \left[-\frac{E_{suggest}-E_{min}}{\sigma_{min}^{2}} \sigma^{2} + E_{suggest} - E_{day}\right] & \sigma < 0 \\ \times \frac{L.w}{Cu.LLF.\eta} & \end{cases} \tag{17}$$

Finally, selling price of energy to these loads is considered 10% lower than the predicted mean energy price of UDN.

5. OPERATIONAL MODELING OF THE MICROGRID BY CONSIDERING UNCERTAINTIES

Microgrids like power grids are required operational scheduling, which generation rate of each units, storage level of batteries, exchange rate of energy with UDN, and controlling strategies of the loads should be determined. In this section a method for optimal operation of a typical microgrid for the next 24 hours has been presented. Also, the proposed DR programs have been considered in that operation scheduling in order to be proven their validation. On the other hand, in order to model and consider the operational uncertainties, Monte Carlo simulation method has been used; so that, many scenarios have been extracted and applied to the operational programs. In fact, in this model the uncertainties of the wind turbine generation, energy price of UDN, demand energy of uncontrollable loads, failure probability of the wind turbine, and disconnection probability with UDN have been considered in the operational planning of the microgrid

4.1. Stochastic modeling of uncertainties

Uncertainty is related to the parameters which have the intrinsic feature of irregularity and uncontrollability. In fact, uncertainty is determined by the distinction of measured, calculated, or estimated with observed value. As described before, in this paper Monte Carlo simulation method which is a numerical method, has been applied to modeling the uncertainties of the microgrid operational planning. A numerical simulation is a process of selecting clusters of the values for parameters of the surveyed system and; then, aggregating results and obtaining a solution. Monte Carlo simulation method is based on generating random samples for probabilistic parameters of the system which each of them is named a scenario. In order to produce random scenarios, a probabilistic distribution function (pdf) is defined for each probabilistic parameter. Some basic methods for generating random samples by pdf include inverse transform method, composition method and acceptance rejection method [40]. Among these methods, inverse transform method is the most useful method which is explained in [20], and has been used in this paper too.

For modeling uncertainties of the presented microgrid, each scenario consists of four main parts including wind speed (ζ^{s}_{w}), energy price of UDN ($\zeta^{s}_{\rho grid}$), demand energy of uncontrollable loads (ζ^{s}_{Pnc}), and connection statues with UDN ($\zeta^{s}_{connection}$) which each of these parts consists of 24 components, represent 24 operation intervals. Also wind turbine failure probability has been considered by setting wind speed to zero in any scenario. In fact, each scenario consists of a vector as $\xi^{s} = \left[\xi^{s}_{w}(t),\ \xi^{s}_{\rho_{grid}}(t),\ \xi^{s}_{P_{nc}}(t),\ \xi^{s}_{connect}(t)\right]$ with the probability (or weighting) of P_r^s which is same for all generated scenarios and is equal to $1/N_s$ (N_s is the number of all generated scenarios). The applied producer of generating random scenarios is as paper [19].

In the Monte Carlo simulation method, many scenarios are generated which each of them must be considered in the operational program. In order to decrease operational program run-time, scenario reduction method is used; so that, similar scenarios are found by Euclidean norm and removed which is described in [19]. This reduction process is continued until the reasonable and desired numbers of scenarios are remained. Then each of these scenarios is applied to the operational program and the results are saved. Finally these saved results are aggregated by statistic models such as normal distribution function. In this paper these aggregated results have revealed the validation of the proposed demand response programs.

1.2. Formulation of the optimal operation for the proposed microgrid

In this section, an optimum operational model for the presented microgrid within the next 24 hours has been presented. Also, by the Monte Carlo simulation method, operational uncertainties have been considered in this model. In this regard, an objective function (OF) with the aim of maximizing total profit has been presented. In fact, by optimizing this OF, microgrid manager could adjust operation strategies including generation rate of the dispatchable units, charging level of ESSs, and exchanged amount of energy with UDN. General structure of the mentioned OF is as follow:

$$OF = Max \sum_{t=1}^{24} \{Income(t) - Cost(t)\} \tag{18}$$

where income(t) and cost(t) are total incomes and costs of the microgrid at time interval t respectively. The total incomes of the presented microgrid consist of selling energy to UDN and to loads. Also the total costs of this microgrid consist of purchasing energy from UDN, and operation costs of microturbines, wind turbines, and ESSs. Therefore the OF of (18), with regard to these descriptions are created as follow:

$$OF = Max \sum_{t=1}^{24} \left\{ \left[P_{grid}(t) \times \rho_{grid}(t) + \left(\sum_{i=1}^{n} P_{nc\,i} \right) \times \rho_{nc}(t) + \left(\sum_{i=1}^{n} P_{heater\,i} \right) \times \rho_{heater}(t) + \left(\sum_{i=1}^{n} P_{light\,i} \right) \times \rho_{ight}(t) \right] - \left[\sum_{j=1}^{x} C_{mt-j}\big(P_{mt}(t)\big) + C_{wt}(t) + C_{bat}(t) \right] \right\} \quad (19)$$

In this equation index i represents relating loads which are connected to busbar i.

Remarks:

- Positive P_{grid} represents the selling energy to UDN, and negative P_{grid} represents the purchasing energy from UDN by the microgrid.
- Positive P_{bat} means discharging ESS and negative P_{bat} means charging ESS.
- Demand power of the uncontrollable loads is determined by Monte Carlo scenarios.
- Demand power of the heater loads and lighting loads are determined by predicted values and controlled by the proposed demand response programs.
- The energy price of UDN is determined by Monte Carlo scenarios.
- The generated power of the wind turbine is determined by (1) with regard to each Monte Carlo scenarios. This Generation is applied in the power balance constraint.

1.2.1. Operational constraints

In order to optimum operation of the presented microgrid by OF of (19), some equal and unequal constraints must be considered too. Part of these constraints is related to the generating units, which have been presented in related section and references but others are systematic constraints that are presented in the following.

1.2.1.1. Power balance

At each time interval, total generated and purchased power must be equal with the total consumed and sold power as follow:

$$P_{grid}(t) + P_{nc}(t) + P_{heater}(t) + P_{light}(t) = P_{mt}(t) + P_{wt}(t) + P_{bat}(t) \quad (20)$$

1.2.1.2. Maximum exchangeable power with UDN

Because of the technical constraints such as capacities of distribution transformer, breakers, or distribution network, the exchanged power with UDN is limited as follow:

$$\left| P_{grid}(t) \right| \le P_{grid}^{max} \quad (21)$$

1.2.1.3. Lower and upper voltage magnitude limits for busbars

Voltage magnitude limits, are often given by very strict standards. High or low voltages contribute to the problems such as damaging end user power devices or instability in the distribution system which leads to the unwanted and economically disadvantages such as partial unavailability of the electricity for end users. In order to prevent from these problems, each node or busbar voltage should be limited as follow:

$$V_i^{min} \le |V_i| \le V_i^{max} \qquad i = 1, \dots, N \quad (22)$$

1.2.1.4. Total active power capacity of the branches

Active power constraint of the distribution lines which is in fact, the current limitation of the branches is resulted from thermal stability of lines. This constraint is specified by cables area of the cross section and is presented as follow:

$$\left| P_{L_{i-j}} \right| \le P_{L_{i-j}}^{max} \quad (23)$$

where $L_{i\text{-}j}$ designated the distribution line between two nodes of i and j.

6. NUMERICAL EXAMPLES

In order to validate the proposed demand response programs, they have been applied and simulated in a typical microgrid. The simulation procedure of this microgrid is as follow:

1. Receiving hourly predicted value for wind speed, temperature, energy price of UDN, demand power of loads.
2. Applying proposed DR programs for described three groups of loads, and determining their demand.
3. Organizing pdf for each of the uncertain factors at all 24 operational intervals.
4. Generating described random scenarios by the Monte Carlo simulation method for all 24 operation intervals.
5. Reducing number of scenarios by the scenario reduction method in order to reduce simulation run-time.
6. Applying all these scenarios separately to the operational planning program of the microgrid and saving all results for decision variables.
7. Aggregating the results by the normal distribution function for total profit of microgrid.

In this regard, a microgrid with the structure of Fig 4 has been considered. This microgrid consists of three busbars. The main busbar (busbar0) is connected to the other two busbars through overhead lines with the specified impedance. Also the wind farm with the capacity of 400kW and a battery bank of 300kWh are connected to this busbar too. On the other hand, this busbar is connected to the upstream distribution network through a transformer post with the rated capacity of 400kW and capability of the bidirectional power exchanging. Moreover, two groups of residential loads consisting uncontrollable loads, heaters and lighting loads situated at both section 1 and 2. The predicted demands of uncontrollable loads and controllable loads before implementing the proposed DR methods have been shown in Fig 5. Furthermore, for more reliability two microturbines connected to the both busbar1 and busbar2. In addition, In order to have adequate reserve in this microgrid, it has been assumed that the minimum charging level of ESS is 75kWh. More detailed specifications of this prototype microgrid have been shown in Fig 4.

In this microgrid, operational intervals have been considered in one hour; as a result, each uncertain factor consists of 24 sections in the random scenarios. In this regard, first 2000 random scenarios have been generated; then, they have been reduced to 200 numbers by the scenario reduction method. In fact, it is assumed that these scenarios would cover all the uncertain attitudes of the microgrid operation. In order to produce random scenarios, distribution functions for each uncertain factor with regard to the presented models in [19] have been calculated and shown by Table 1. In this table, mean values of the uncertain factors are predicted value of them. Moreover, random scenarios for the failure probability of the wind turbine and disconnection probability for UDN, have been generated according to the presented model in [19].

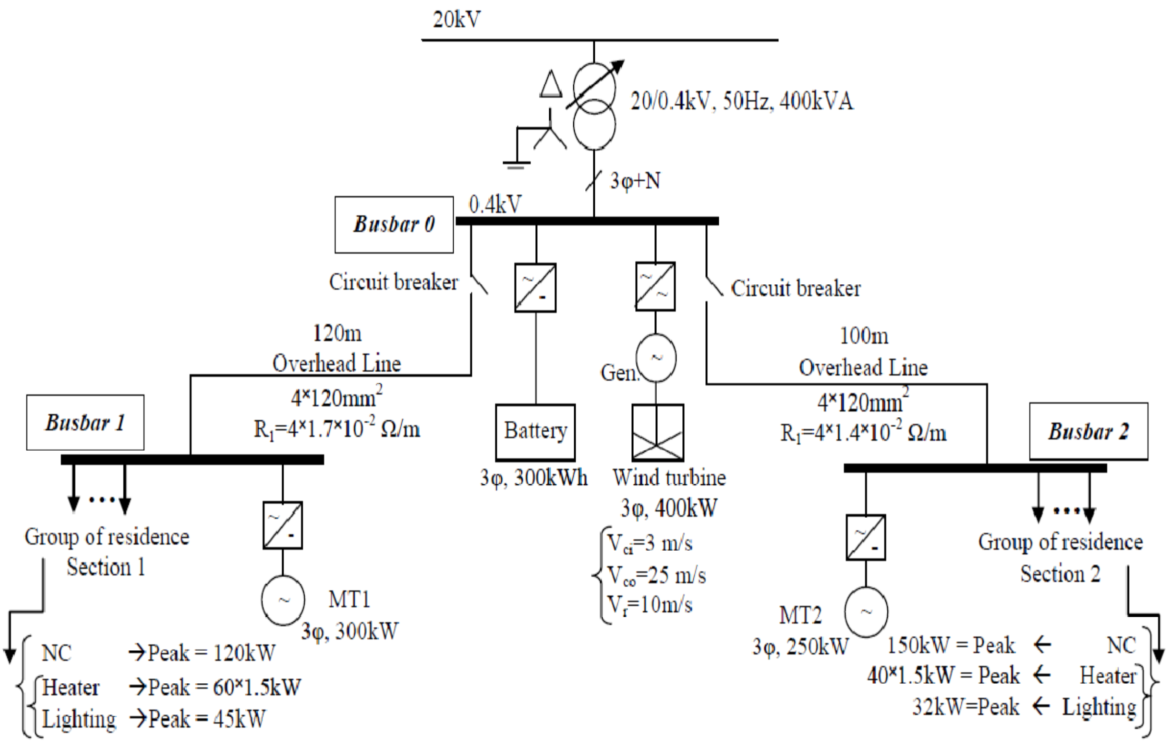

Fig. 4 : General network structure of proposed microgrid

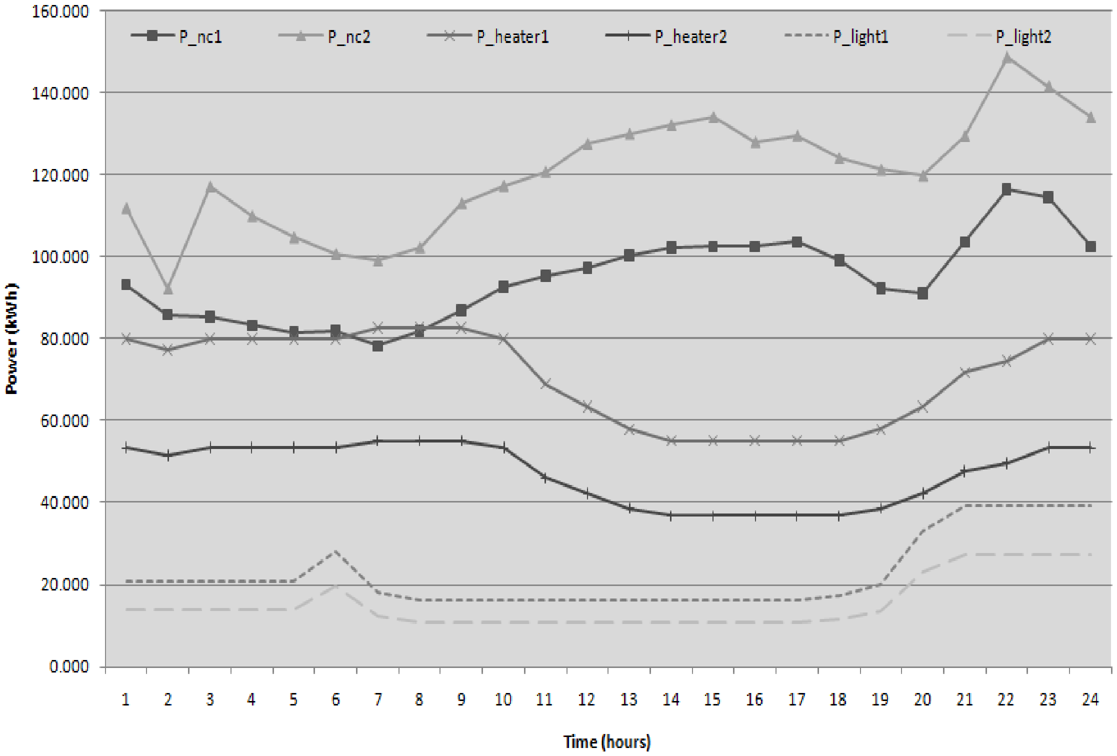

Fig. 5 : predicted demand of microgrid's loads

Table 1 : Mean and standard deviation values of wind speed, energy cost of UDN, and demand of critical loads

Period (hour)	Wind speed		Energy cost ($/kWh)		NC Loads (kW) Section 1		NC Loads (kW) Section 2	
	Rayleigh Distribution		Normal Distribution		Normal Distribution		Normal Distribution	
	$\bar{V}\ (m/s)$	Scale parameter	Mean	St. De.	Mean	St. De.	Mean	St. De.
1	3.3	3.70	0.0254	0.0092	77.62	4.38	89.55	5.26
2	2.6	2.91	0.0145	0.0097	71.53	4.03	73.89	4.84
3	2.8	3.16	0.0146	0.0083	72.12	3.57	93.74	4.28
4	2.9	3.27	0.0184	0.009	69.33	3.30	87.99	3.96
5	3.7	4.17	0.0144	0.0079	67.84	3.30	83.81	3.96
6	3.0	3.37	0.0113	0.0108	68.14	3.11	80.56	3.74
7	2.7	3.01	0.0048	0.0083	65.18	2.01	79.41	2.41
8	1.0	1.07	0.0098	0.0079	68.22	1.53	81.87	1.84
9	2.1	2.37	0.0144	0.0056	72.36	1.43	90.44	1.72
10	3.6	4.00	0.0232	0.0077	77.20	1.81	93.84	2.18
11	4.8	5.38	0.0313	0.0099	79.46	1.94	96.55	2.33
12	6.0	6.77	0.0331	0.0231	81.03	2.57	102.04	3.09
13	7.2	8.08	0.0281	0.0191	83.66	3.57	103.99	4.29
14	8.7	9.79	0.028	0.0165	85.06	4.04	105.67	4.84
15	9.2	10.36	0.0203	0.0166	85.34	4.33	107.20	5.20
16	9.9	11.11	0.0272	0.0191	85.32	4.47	102.39	5.37
17	9.1	10.21	0.0326	0.0197	86.33	4.53	103.59	5.44
18	8.3	9.40	0.0275	0.0094	82.70	3.15	99.24	3.78
19	7.9	8.85	0.0262	0.0109	76.83	4.26	97.00	5.11
20	6.9	7.80	0.033	0.0149	75.85	5.78	95.83	6.93
21	6.2	7.03	0.0348	0.0102	86.30	4.11	103.56	4.93
22	5.3	6.02	0.055	0.0079	97.08	2.41	118.90	2.89
23	3.7	4.14	0.0395	0.0116	95.35	4.24	113.22	5.09
24	3.1	3.44	0.0148	0.0096	85.32	4.39	107.19	5.91

In this model, OF of (19) by considering its constraints has been applied for the optimal operation of it. This OF has been optimized by the partial swarm optimization method. This process is applied according to the described procedure in the beginning of this section. Also, decision variables consist of microturbines generation level, exchanging energy with UDN and energy storage level of ESS.

Typical simulation for each proposed controlling methods of loads and effect of them on the operation of the microgrid are investigated as below.5.1. Simulating the proposed DR programs

5.1.1. Heating Loads

In this microgrid there are one hundred heating loads, each one with 1.5kW rated power consumption. Every one of these heaters has been installed at a house with about 200 square meter area. In this place, heat exchanging is done with around walls and windows which are formed 20% of walls. Also the desired temperature for residents is 24^{oC};

however, they can tolerate scope of 22^{oC} to 27^{oC}. Furthermore, there are 60 implemented heater loads on Busbar1 and 40 on Busbar2. In addition, the predicted outside temperature has been shown in Fig 6.

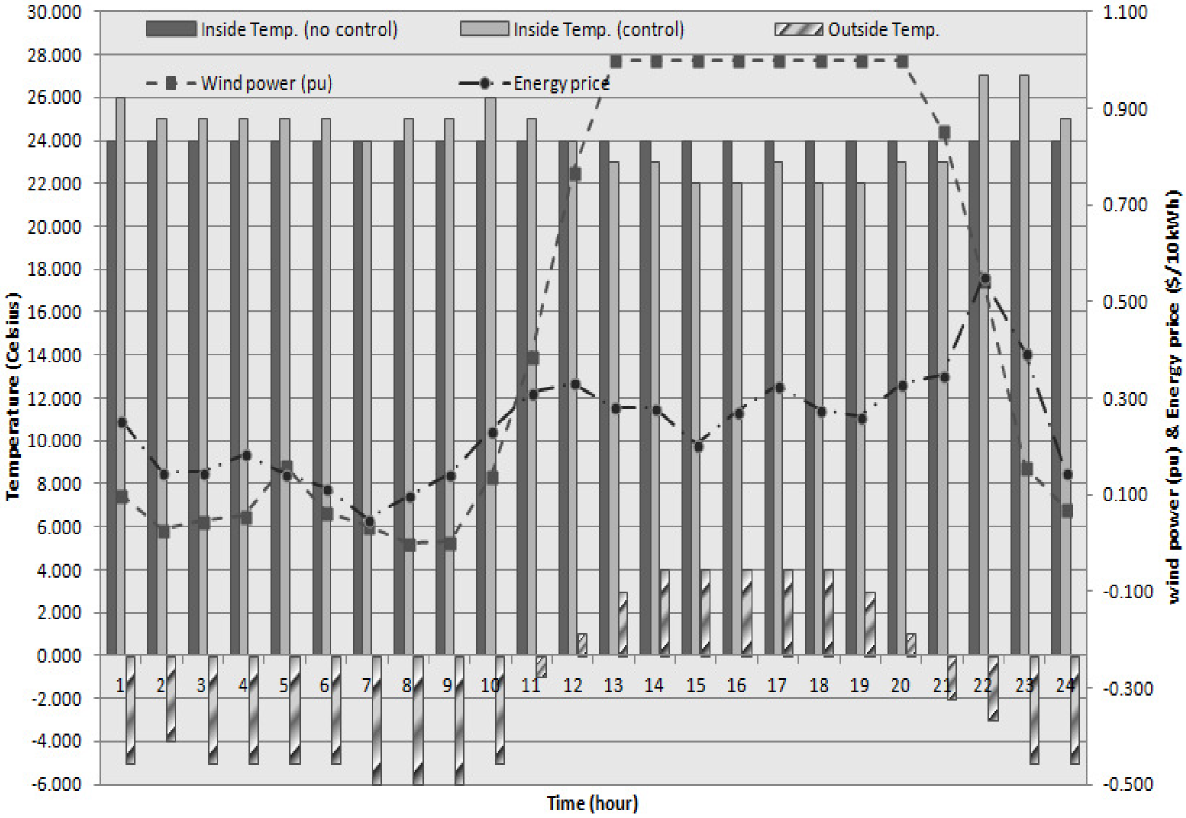

Fig. 6 : Inside temperature before and after implementing the proposed DR method for heating loads and predicted outside temperature

According to the proposed DR method for these loads, the inside temperature is related to wind energy and energy price of UDN which is exhibited by Fig 6. Moreover, for better realization, Fig 7 demonstrates consumed power of these loads in section 1, before and after implementing the proposed DR program. These values are related to the mean scenarios of the wind speed and energy price of UDN which are also shown by this figure. Due to this figure, when the wind generation is more than and the energy price is lower than their mean values, the inside temperature is adjusted more than the desired temperature which results in saving energy as thermal energy. However, if these uncertain factors are vice versa, the inside temperature is adjusted less than the desired temperature in order to decrease consumption level of these loads. In fact, the inside temperature is somehow adjusted to meet the required controlling goals. In a word, the consumed power of these loads is coupled with the wind energy and energy price of UDN as it is shown by these figures.

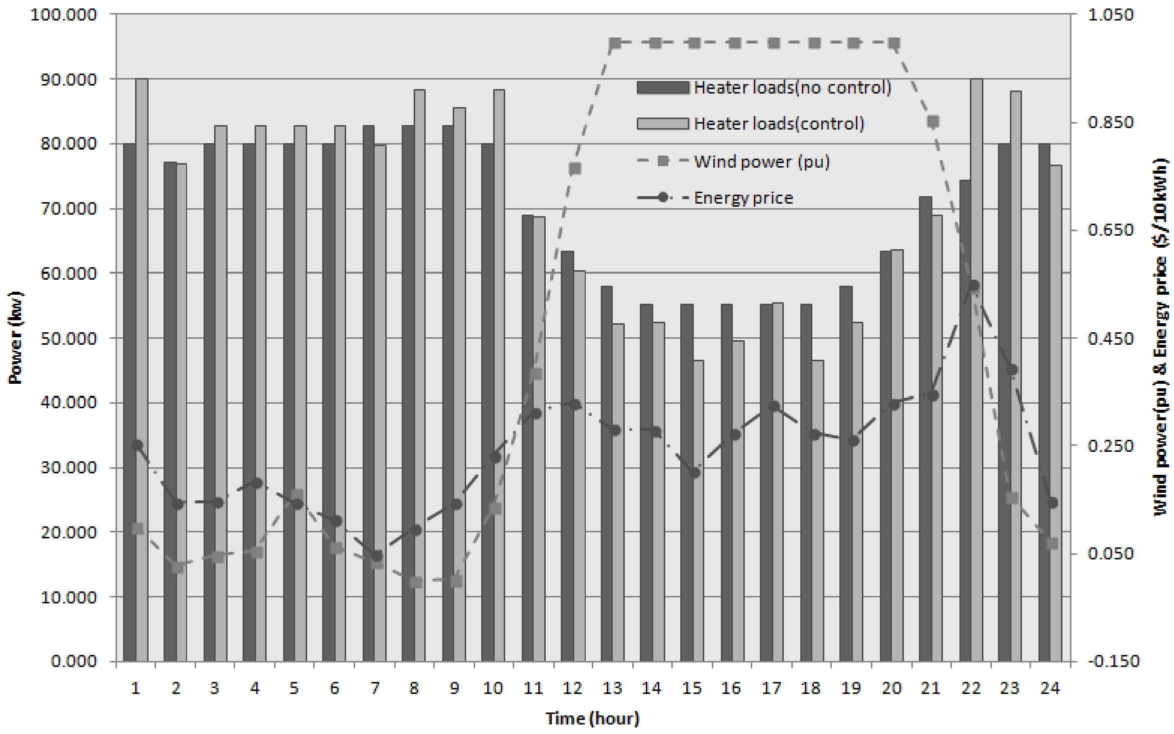

Fig. 7 : Total demand of heating loads in section 1 before and after implementing the proposed DR method for the mean values scenario

Table 2 : Lighting specification and the required lighting flux for desired places

place	proposed illumination level (Lux)	minimum illumination level (Lux)	required flux on surface (Lm)	type of lamp	number of lamps	η(Lm/W)	DF(%)
living room	200	70	24193	compact fluorescent (57W) 4300Lm	6	75.44	60
kitchen	200	100	8744	compact fluorescent (57W) 4300Lm	3	75.44	30
bedroom	100	50	3278	compact fluorescent (26W) 1800Lm	2	69.23	30
corridor	100	40	10582	fluorescent (39W) 3100Lm	4	79.49	0
reading room	500	300	3809	compact fluorescent (57W) 4300Lm	1	75.44	70
Outside (pavement)	6	2	3113	compact fluorescent (42W) 3200Lm	1	76.19	100

5.1.2. Lighting Loads

In this typical microgrid, all used lamps are in type of compact or conventional fluorescent lamps. Also, it has been supposed that, this microgrid consists 30 living rooms in section 1 and 20 in section 2, 30 kitchen in section 1 and 20 in section 2, 75 bedrooms in section 1 and 75 in section 2, 120 corridor lights in section 1 and 80 in section 2, 30 reading room in section 1 and 20 in section 2 and finally 120 outside lights in section 1 and 80 in section 2. Table 2 shows the lighting specifications and calculated results of the required lighting flux for each of the given places, which was extracted from lighting references. In this table, amount of the daylight illumination which enters to the desired place is shown by DF and is calculated as (24). Moreover the illumination of daylight in this simulation has been shown by Fig. 8.

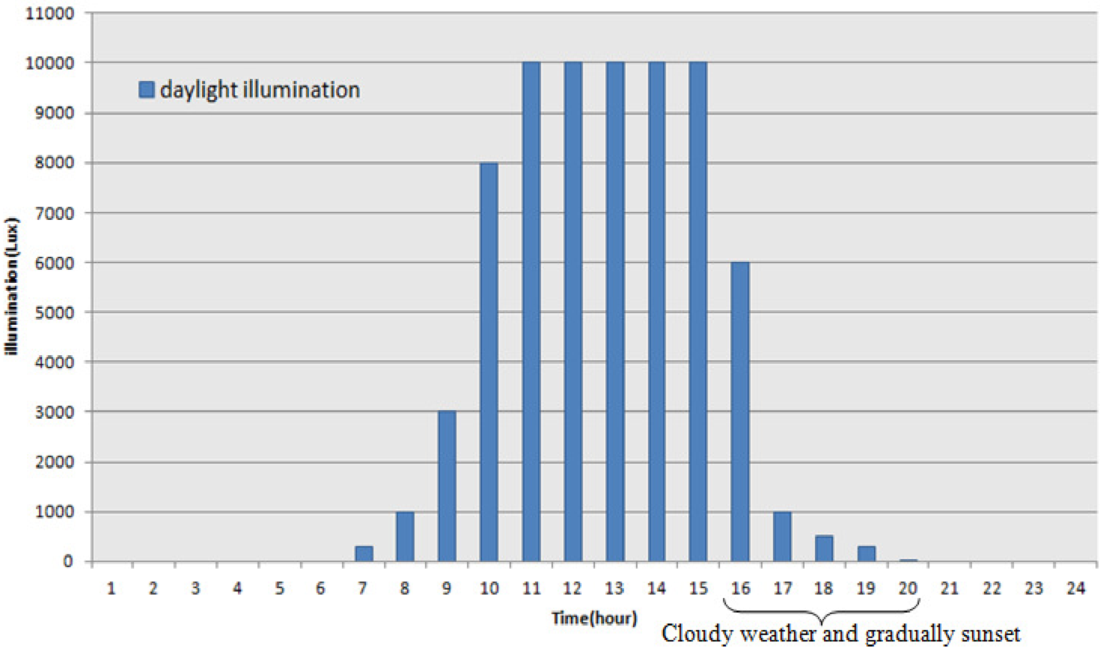

Fig. 8 : Predicted illumination of daylight for each time interval

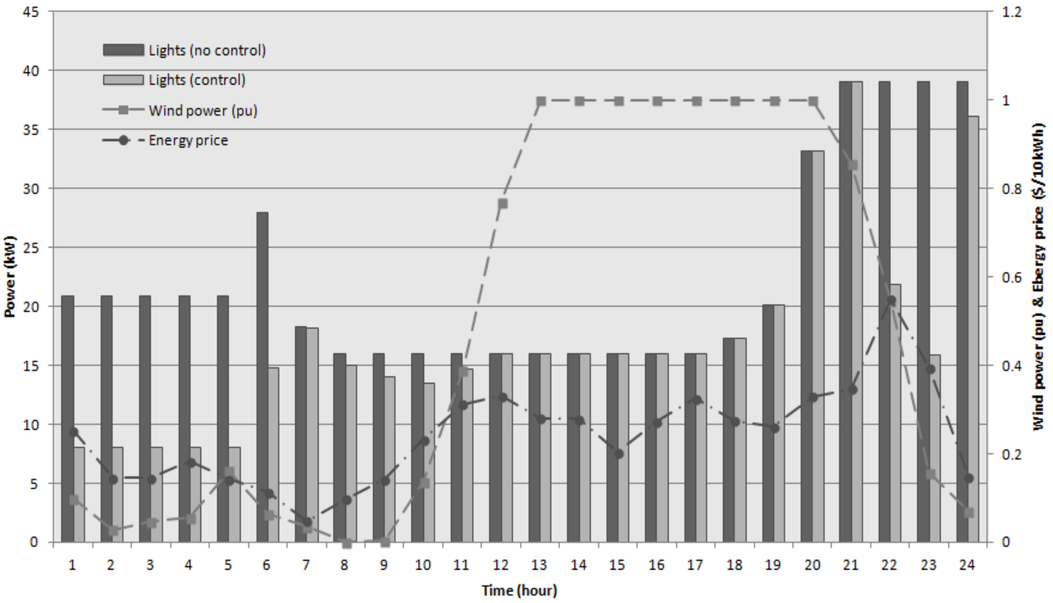

Fig. 9 : Total demand of lighting loads before and after implementing the proposed DR program for mean values scenario

$$DF = \frac{illumination\ of\ daylight\ at\ the\ desired\ place}{daylight\ illumination} \tag{24}$$

According to the proposed DR method for these loads, their demands are coupled with wind energy and energy price of UDN. For better realization, Fig. 9 shows the total demand power of these loads before and after implementing the proposed controlling method with regard to the mean values scenario of wind energy and energy price. According to this figure, when wind energy is reduced and energy price of UDN is increased, the consumed energy of these loads has been reduced; however, in other time intervals the consumed energy of these loads is almost equal with the consumption levels before controlling them

5.2. Simulating the operation of the presented microgrid

In this simulation, in order to validate the proposed DR methods, two operational cases for the presented microgrid have been considered, and the results have been compared.

5.2.1. Case 1

In this case, none of the proposed DR programs have been implemented in the operation of the typical microgrid. Therefore, all microgrid loads have been operated in their normal condition. Moreover, all uncertainties have been engaged in the operation of the microgrid by Monte Carlo simulation method which was described before. Respectively, random scenarios were generated with regard to table 1; then, they were reduced by scenario reduction method. Next, these scenarios were simulated and operational results have been aggregated by the normal distribution function. Fig. 10 shows the approximated normal distribution function for the total operation profit of the microgrid. According to this figure, mean profit of the microgrid operation in this case is 97.48$.

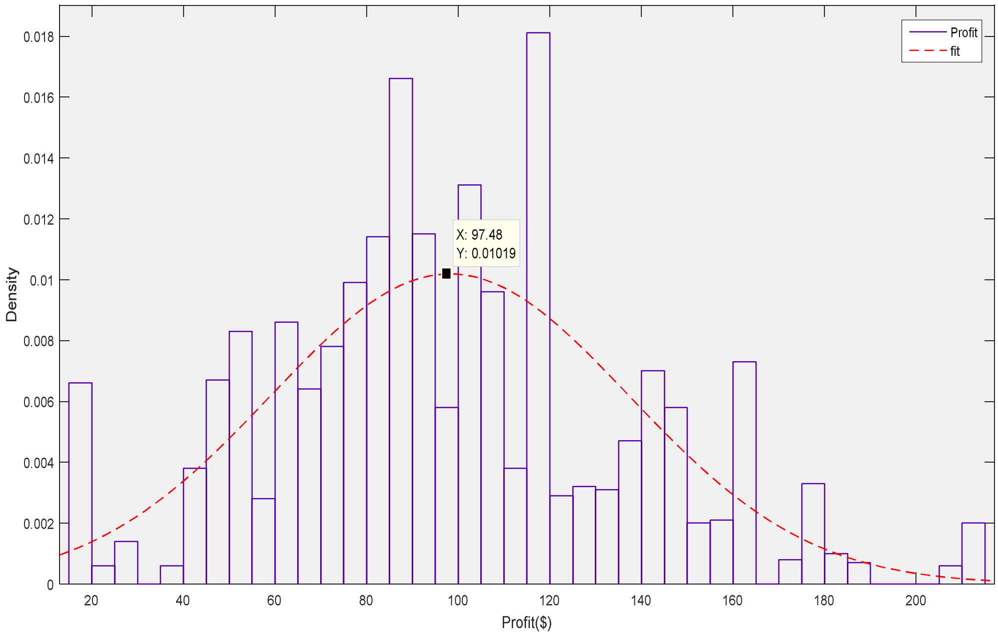

Fig. 10 : Probability distribution function for total operation profit of microgrid in Case 1

5.2.2. Case 2

In this case, microgrid specifications are similar to the previous case in that all uncertainties have been modeled by the Monte Carlo simulation method. Furthermore, in order to show validity of the proposed DR methods for heater loads and lighting loads, they have been implemented according to the mentioned assumptions in the operation of the microgrid. Fig. 11 shows the probability distribution function of the total operational profit of the microgrid in this case, which its mean value is 120.9$. By comparing this value with the previous case, it can be deduced that microgrid operation profit has been increased significantly. Furthermore, the high values of the profit distribution function are increased. Also, it is obvious that, the low section of the distribution function has been shrunken in regard to the previous case function. Thus, by implementing the proposed DR methods, the operation loss risk of the microgrid has been reduced.

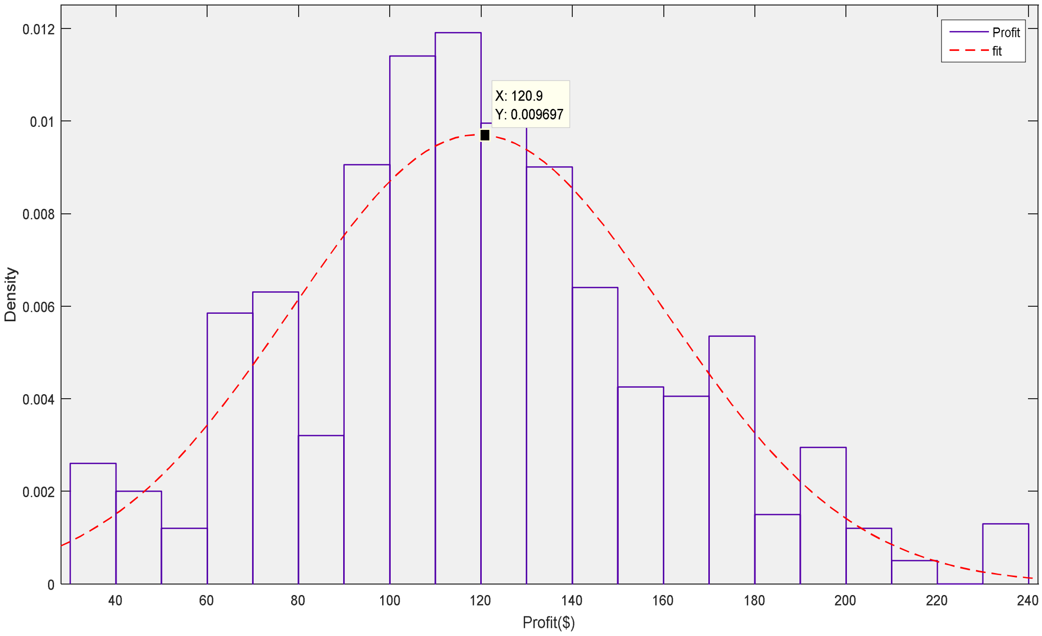

Fig. 11 : Probability distribution function for total operation profit of microgrid in Case 1

7. CONCLUSIONS

In this paper, new demand response programs for the typical domestic loads within the framework of the smart microgrids, were proposed. In this regard, total loads of the microgrid were classified into two groups of the energy storage capability and curtailment capability. Next, each of these groups was represented by a typical load and for each of them a new DR method was proposed. In these methods, consumed energy of loads is coupled to the wind power and energy price of upstream distribution network (UDN). In other words, these methods are a tool to deal with the operation uncertainties of microgrid such as wind power and energy price of UDN. Moreover, in these methods the welfare level of consumers and discount in their energy bill were considered. Finally, these methods were considered in the operation of a typical microgrid.

The desired microgrid of this paper includes wind turbine representative for non-dispatchable resources and microturbine representative for dispatchable resources. In this model, by Monte Carlo simulation method, uncertain factors including wind generation, energy price of upstream distribution network (UDN), demand power of critical loads, disconnection probability from UDN, and failure probability of wind turbine were considered in the operation program. This method could cover all probabilistic conditions and finally presents a probability distribution function for each of the decision variables which could be used in the operational scheduling of the microgrid. Also, in order to optimize the operation of this microgrid, PSO method was used which achieves to the optimum point in continuous environmental of this problem with many decision variables at a relatively short time.

In this paper, various scenarios and cases were simulated and the obtained results were investigated. These simulations showed that by implementing these DR methods, not only the variations of the non-dispatchable resources and energy price of UDN could be dealt, but also the operation profit of microgrid was increased. Furthermore, these methods were caused to reduce the risk of the less operational profit of the microgrid. For the future works, it is suggested to consider a model for the electric vehicles as V2G method and applied it in the operation of this microgrid which also could be used to deal with the uncertainties

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