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# *Optimal Operation of Renewable Energy-based Grid-connected Microgrid*

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*Abstract*— **In recent years, the utilization of renewable energy sources in supplying electricity energy has resulted in more reliable and efficient operation with better power quality and flexibility especially distribution network. However, from the operation and management points of view, the high utilization of the distributed generation can cause unexpected challenges which a part of them is addressed by microgrids (MGs) problem. In this paper, for analysis some of unexpected challenges such as uncertainty in wind and sun power, the optimal operation of grid-connected MG during a specific day and with considering a proper mathematical model for simplifying the optimization program, is investigated. The considered MG consisted of wind turbines, Photovoltaic (PV) systems, battery energy storage, diesel generator and local loads. The wind speed and sun irradiation data are obtained for a rural village which is located in $47^0.5^{'}$N and $35^0.59^{'}$E in Kurdistan province in Iran. By applying the demand response (DR) strategy to the optimal operation program, the results are compared with typical operation condition (non-DR) of the MG. In addition, the impacts of uncertainties such as wind speed and sun irradiations variations on the optimal operation of the MG are investigated. The optimal sizes of the MG components are obtained with HOMER software.**

***Keywords-component; Optimal operation; Microgrid; Renewable energy, Demand response; Uncertainty***

## I. INTRODUCTION

In recent years, the utilization of alternative energy sources such as wind, biomass, solar, hydro and etc. has become more widespread mainly due to the needs for better reliability, higher power quality, less cost, more flexibility, and smaller environmental foot-prints [1,2]. On the other hand, distributed generations (DGs) such as PV, micro turbines, fuel cells and storage devices are expected to play an important role in future electricity supply and low carbon economy [1,2]. However, high penetration of DGs into the grid will bring new challenges from the safe and efficient power system operation points of view. Some of these challenges can be addressed by MG which is defined as an aggregation of DGs, electrical loads and creating interconnection among themselves ad with distributed network as well [2-5]. Therefore, in recent years, different methodologies with different objectives have been applied to manage and control the MGs operation with different conditions. In the economical point of view, distributed electricity generation provided by MGs can brings about more benefits such as higher efficiency, loser pollution and losses which are performable with using renewable energy sources (RESs) as distributed generators including wind turbines and PVs [5]. On the other hand, due to the environmental concerns and pollutant emission from conventional fossil fuel units, the governments have been encouraging investors to install more and more (RES) for supplying the grid demand. Although, determining the type of utilized RESs are considered based on geographic conditions and new optimal planning methodologies [7,8]. But, for rural and remote areas which are isolated from the utility grid, the combination of several RESs such as wind , sun irradiation, and etc. can provides the grid utility owners and customers various benefits in both point of view (environmentally and economically) including; lower energy cost, higher service reliability, lower environmentally foot-print, and power quality [3,7,15].

This paper focuses only on the economic aspects of the microdrid optimal operation. As mentioned previously, reduction in operation costs and environmental emissions have been attempted in many research works, with focusing on management strategies which need optimization algorithms and efficient methods. In recent year several studies are carried out to find optimal solution for MGs from both environmentally and economically perspective. The energy storage units are used along with the distributed generation ones to make the operation of MGs more reliable and economical [5,12,14]. The utilization of energy storage systems (ESSs) will be highlighted when the microgrid switches to the isolated mode or exposes to a wide range of uncertainties in which imposes by RESs. Several studies have been focused on optimizing and operation management of the hybrid renewable energy systems [1-5], [7-16]. The authors in [15], proposed an optimization procedure to optimal dispatch of distributed generations and energy storage systems in an isolated microgrid with the objective of minimizing operating cost and environmental emission, simultaneously. In [14], the authors proposed a two-objective optimization function (profit maximization and cost maximization) for a power generation company with integrated wind and Compressed Air Energy System (CAES). They also analysis the impacts of considering or not considering of the capital cost on the operational profits and total load serving costs. On the other hand, managing uncertainties which is arisen from utilization of renewable generation and load demand prediction are considered as objective for optimum operation of hybrid renewable energy sources. The author in [16], applied the Point Estimate Method (PEM) to optimize a microgrid by modeling and considering uncertainties in the renewable power generation, the energy demand and the market prices.

In this paper, the optimum sizes of hybrid renewable based grid-connected microgrid are obtained from HOMER software. Then, by defining proper mathematical model and microgrid component's constraints for the optimization program, the impacts of uncertainties such as variation in wind speed and sun irradiation are analyzed. Furthermore, by applying demand response (DR) strategy, the results are compared with non-DR one. Hence the main motivation of this research work can be outlined as follows:

- Determining the optimal size of grid connected hybrid microgrid with HOMER software.
- Optimal operation of hybrid grid connected microgrid consisted of diesel generator, PV, battery, power converter, and wind turbine.
- Investigating the impacts of variation in wind speed and sun irradiation on the operation cost of the considered microgrid during a specific day.
- Studying impacts of applying demand response on the operational cost of the microgrid during a specific day)

The rest of paper is organized as follows: Section II presents a description of microgrid structure and components. In Section III, a proper mathematical model for microgrid components and their corresponding constraints are introduced to perform optimal operation on the microgrid. In Section IV, the simulation results from applying demand response (DR) and non-DR are compared; in addition to that, the impacts of applying uncertainties such as wind speed and sun irradiation variations on the optimal operation of microgrid are investigated in this section. In Section V the conclusion of this research work is given.

## II. UNDER CONSIDERATION MICROGRID

The under consideration microgrid is comprised of wind turbines, photovoltaic (PV) arrays, diesel generator, batteries, power converter, and local loads (electricity consumption of a rural village) which is connected to the external grid. The optimal size of the each microgrid components is obtained by HOMER software and is as follows: (see Table 1).

Table1. Obtained optimal sizes of microgrid components

| **Wind Turbines (Kw)** | **PV (Kw)** | **Diesel Generator (Kw)** | **Power Converter (Kw)** | **Battery (Kw)** | **External Grid (Kw)** |
|---|---|---|---|---|---|
| 220 | 212.6 | 200 | 100 | 100 | 330 |

The under studying microgrid is a real rural village in which located in $35^0.59^{'}$ N , $47^0.5^{'}$ Kurdistan province in Iran [9]. The local load of the microgrid, is the electricity consumption the rural village which is comprised of the 200 houses (considering 5 persons as an average living in each house), boarding clinic, mosque, double shifted school and agricultural electricity consumption (related to electric water pumps). The hourly electrical load profile for **July** month is shown in Fig. 1. The maximum consumed energy during a day (among 12 months) is belong to this month, and its total consumption and highest peak demand are 8446 Kw and 583 Kw, respectively.

The 24-hour wind turbine and PVs output powers, and also hourly wind speed and sun irradiation variation for the given geographic area are illustrated in Figs 2-5. The wind speed and sun irradiation data are given from [9] for the mentioned rural village.

Three tariffs are considered for the electricity purchasing rate from the external grid (0.006 $, 0.012 $, 0.024 $, for the low, medium, high demand peak, respectively [17]. Also, in [17], the electricity sell rate from microgrid to the external grid is considered constant and is about 0.06 $ during the 24 hours. In Table 2, the corresponding details for different rates of selling and purchasing electricity to/from external grid and different statuses of demand load are shown.

It must be noted that one dollar ($) has been equaled to 350000 Iran's currency units (Rial). That’s why the values for selling and purchasing electricity are become so low.

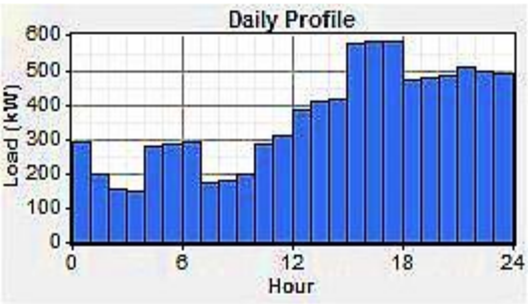

Fig. 1. Hourly electrical load profile for **July** month for microgrid.

Table 2. Information about sell/purchase electricity to/from external grid

| Demand Status | Purchase from the Grid ($/kw) | Sell to Grid ($/kw) | Hour |
|---|---|---|---|
| Low Peak | 0.012 | 0.052 | 24 p.m. to 8 a.m |
| Medium Peak | 0.024 | 0.052 | 8 a.m. to 18 p.m. |
| High Peak | 0.048 | 0.052 | 18 p.m. to 24 p.m. |

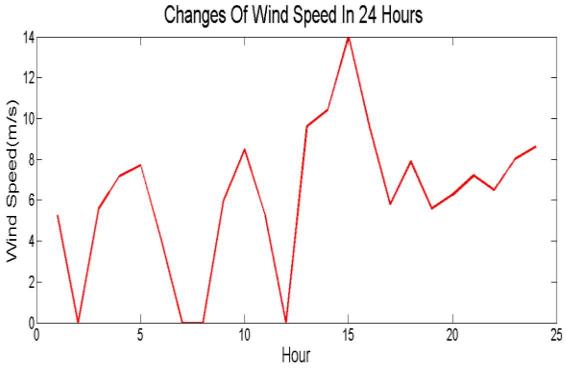

Fig. 2. Wind speed variation in the village area for 24 hours.

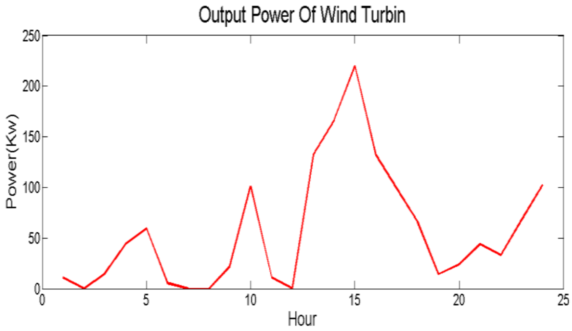

Fig. 3. Output active power variations of wind turbines for the given wind speed for 24 hours.

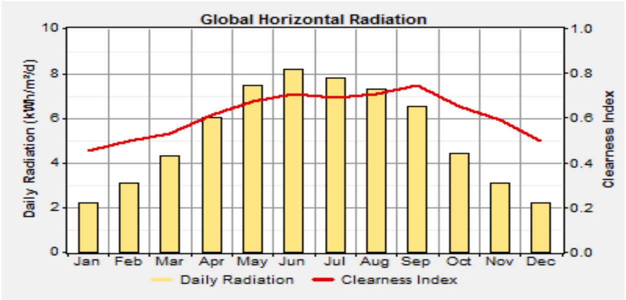

Fig. 4. Sun irradiation profile for the considered rural area.

Table 3. Description of the used symbols

| | |
|---|---|
| $DR$ | Demand Response |
| $P_{Gridin}$ | Grid Purchased Power per Hour (kw) |
| $P_{Gridout}$ | Sold Electricity to the Grid (kw) |
| $Price_{Gridin}$ | Grid Purchase Cost(Rial) |
| $Price_{Gridout}$ | Grid Sale Cost(Rial) |
| $Price_{Fuel}$ | Diesel Generator Fuel Cost (Rial) |
| $F(t)$ | Consumed Fuel(Liter) |
| $\eta_{DG}$ | Diesel Generator efficiency |
| $\eta_{AC/DC}\eta_{DC/AC}$ | Power Convertor Efficiencies |
| $Battery_{Max}$ | Battery Maximum Power (kw) |
| $P_{Charge}$ | Battery charged Power (kw) |
| $P_{decharge}$ | Battery Discharged Power (kw) |
| $SOC$ | State of Charge of Battery |
| $P_{Load}$ | Consumption Load Power (kw) |
| $P_{WT}$ | Wind Turbine Power Production (kw) |
| $P_{PV}$ | Photovoltaic system Power Production (kw) |

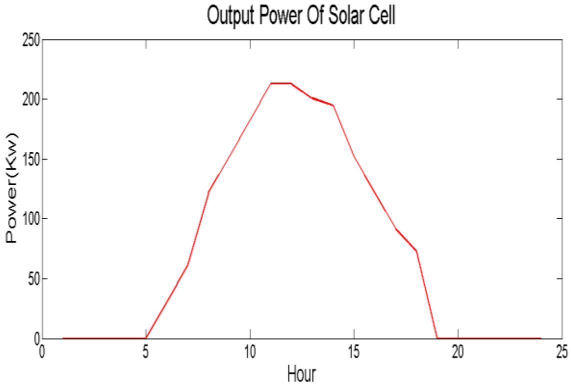

Fig. 5. Output power variations of PVs for given sun irradiation for 24 hours.

## III. MATEMATHICAL MODELLING

A microgrid with functional mathematical model which is connected to a main grid must consider all constraints for the microgrid components. These constraints must be defined in order to simplify the final optimal utilization as much as possible and also make it applicable [11]. The main motivation of this paper is to minimizing the operational cost of the described microgrid during a specific day in July. It's noteworthy that the presented models can be generalized for optimal operation purposes in other days of year and also can be used in other studies. In another word, determining the amount of production microgrid components including diesel generator, electricity exchange between external grid and microgrid, and charge/discharge of battery energy storages is the main objective of this mathematic modeling. The symbols which will be used in this section presented in Table 3.

## A. *Objective Function*

Having the capability to exchange power with the external grid, in equation 1, the objective function tries to minimize the total operation cost which is results of microgrid power suppliers' generation for the next 24 hours.

$$Objective\ Function = \left\{ \begin{array}{l} \sum_{t=1}^{24} P_{Gridin}(t) \times Price_{Gridin} \ldots \\ -P_{Gridout}(t) \times Price_{Gridout} \ldots \\ +F(t) \times Price_{Fuel} + O\ \&\ M \end{array} \right\} \quad (1)$$

## B. *System Constraints*

### 1) *Power Balance Constraint*

System constraints consist of power balance constraint in AC bus, and other technical issues which are relating to the microgrid components. The AC bus constraint can be seen in equation 2.

$$Power\ Balance\ Constraint = \left\{ \begin{array}{c} P_{WT}(t) + P_{DG}(t) + P_{Gridin}(t) \ \ldots \\ +P_{PV}(t) \times \eta_{DC/AC} + P_{dcharge} \times \eta_{AC/DC} \ \ldots \\ = P_{Gridout}(t) + P_{Charge}(t) \times \eta_{AC/DC} + P_{Load}(t) \end{array} \right\} (2)$$

### 2) *Grid constraitns*

The maximum allowable for exchanging power between grid and microgrid is limited to 330 Kw. This value is obtained by optimal planning of the microgrid with HOMER software. The grid constraints are shown in equation 3.

$$Grid\ Constraints = \left\{ \begin{array}{l} 0 \le P_{Gridmax} \le 330 \\ X_{Giridin}(t) + X_{Gridout}(t) \le 1 \\ P_{Gridin} \le X_{Gridin} \times P_{Gridmax} \\ P_{Gridout} \le X_{Gridout} \times P_{Gridmax} \end{array} \right\} \quad (3)$$

### 3) *Diesel Generator Constraint*

The amount of diesel generator power production cannot exceed from 200 Kw per hour. Besides, 20 Kw as the ramp-rate (sudden increase or decrease in output power) value of diesel generator is applied to the optimization program (see equation 4) [10].

$$Diesel\ Generator\ Constraints = \left\{ \begin{array}{l} P_{DG}(t) \le P_{DG\max} \\ P_{DG}(t+1) - P_{DG}(t) \le RR \\ P_{DG}(t+1) - P_{DG}(t) \le RR \\ P_{DG}(t) = F(t) \times HR \times \eta_{DG} \end{array} \right\} \quad (4)$$

### 4) *Battery Constraints*

The battery energy storage cannot be charge and discharge, simultaneously. In addition, the amount of charge/discharge must be considered based on battery capacity. The mathematical description of battery constraints are presented in equation 5.

$$Battery\ Constraints = \left\{ \begin{array}{c} X_{Charge}(t) + X_{Decharge}(t) \le 1 \\ P_{Charge}(t) \le X_{Charge}(t) \times P_{ChargeMax} \\ P_{Decharge}(t) \le X_{Decharge}(t) \times P_{DechargeMax} \\ SOC(t+1) = SOC(t) \ldots \\ +\left(\frac{P_{Charge}(t) \times \eta_{AC/DC} - P_{Decharge}(t) \times \eta_{DC/AC}}{Battery_{Max}}\right) \\ SOC_{Min} \le SOC(t) \le SOC_{Max} \end{array} \right\} (5)$$

### 5) *Photovoltaic Panels and Wind Turbines constraints*

Based on the given data from [9], the output power of wind turbines and photovoltaic systems can be limited in to two ranges as indicated in equations 6 and 7.

$$Wind\ Turbines\ Constraint = 0 \le P_{WT}(t) \le 220Kw \quad (6)$$

$$PV\ Constraint = 0 \le P_{PV}(t) \le 212Kw \quad (7)$$

### 6) *Demand Response Constraint*

For applying demand response to the optimal operation program, the following constraint is considered.

$$DR = \left\{ \begin{array}{c} \sum_{t=1}^{24} DR(t).Load\ (t) = \sum_{t=1}^{24} Load\ (t) \\ 0.8 \le DR(t) \le 1.2 \end{array} \right\} \quad (8)$$

# IV. RESULTS AND DISCUSSION

The mathematical model used in this research is MIP model, which is run in GAMS software by CPLEX Solver. In this section, first, the simulation results will be investigated without considering DR in optimization program. Then, by applying the DR constraints, the optimization program will be run again and their results will be compared with non-applying of DR. Finally, the impacts of uncertainties such as wind speed and sun irradiation variations on the optimal operation results of microgrid will be discussed.

## A. *Simulation Results without applying DR*

In this subsection, the optimal operation results (related to power changes of microgrid components) of microgrid which is in its normal operation mode, are indicated in Fig. 6.

The value for the total operation cost of the microgrid is Rials 30127965.5 (equivalent with $ 86.08).

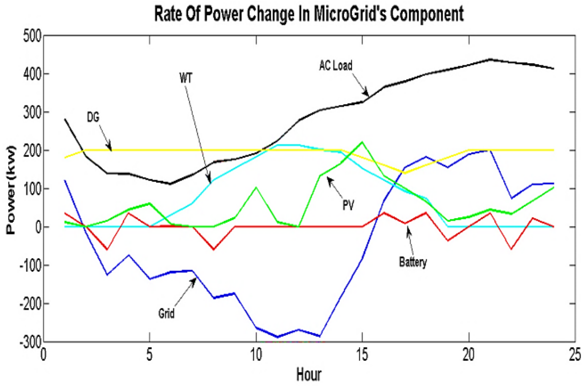

Fig. 6. Rate of power change in microgrid components during a day.

As shown in Fig. 6, in the curve corresponding to the exchanged power between microgrid and external grid (grid curve), with the passing of the time, the amount of purchasing power from the grid is reduced. Therefore, the negative values in grid curve shows selling power to the external grid and the positive values indicate purchasing power from the main grid. Similar to the grid cure analysis, the values for batteries state of charge (SOC) are reduced during the operation of the microgrid. In another word, the positive values for SOC show charging of the batteries and negative values are associated to the discharge of the batteries during the 24-hour.

Considering the above explanations and with further investigation of the Fig. 6, in the first few hours, diesel generator uses maximum allowable generation (due to the absence of PV generation). These conditions to be continued until PV to be capable generate its power. After the presence of PVs along with wind turbines, the diesel generator keeps its generation and additional power will be sold to the external grid. In one hand, with reaching the end of the day and losing the output power of PV, and on the other hand, with increasing the total power demand (see load curve), the diesel generator reaches its maximum allowance power, again.

In the first few hours of the mid-night and with decrease in the demand load, the amount of power sell form microgrid to the main grid will be increased. The maximum amount of sell is associated to the 9 a.m. to 13 p.m. hours. Due to the presence of wind turbines power along with PVs (in its maximum output power) and also the lower amount of demand load in compared to the amount of demand after 13 p.m., we can see the maximum amount of power which is sold to the main grid.

### *B. Simulation Results with Applying DR*

Demand Response is a strategy in which the system operators encourage the consumers to decrease in the amount of their electricity consumption with the hope of shifting loads from the peak hours to the low or medium peak demand hours. In this procedure, not only the customers receive profits by shifting their consumptions from peak demand hours (with higher electricity costs) into outside peak demand (with lower electricity costs) during the day, but also the amount of microgrid operation profits will be increase; because, the microgrid's owners do not need to expand and install more power suppliers to meet the microgrid peak demand in peak hours-only. In this paper, maximum allowable shifting of power is considered 20% of the total load for each hour.

According to Fig. 7, by applying the DR, the microgrid capability for selling power to the external grid is decreased. Consequently, the microgrid has decreased the amount of its dependency on diesel generator power generation (due to having higher fuel cost for diesel generator than purchase power cost from the main grid) and instead has increased the amount of purchasing electricity in the low and medium peak demand. It's noteworthy that by applying DR, the SOC and consequently charge/discharge of the batteries has improved.

In Fig. 8, the modified load curve (considering DR in optimization program) is compared with the normal load curve. As expected, the total microgrid operation cost is decreased from Rials 3012796.5 in normal operating condition (equivalent to $86.08), to Rials 2556536.5 (equivalent to $73.04) with applying DR. According to Fig. 8, with modification of load curve, the load pattern is changed in a way the power consumption is shifted into lower and medium peak demand hours so that brings more satisfying both microgrid operators and costumers.

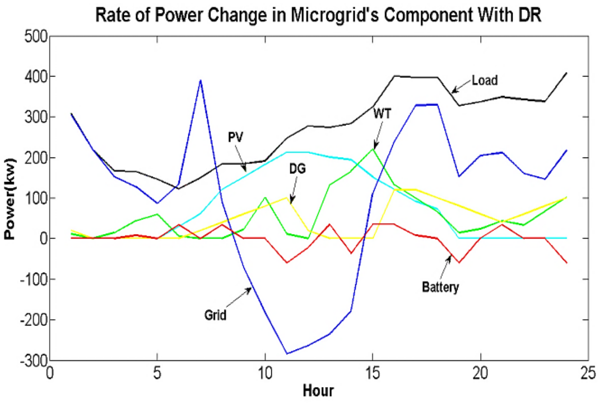

Fig. 7. Rate of power changes in microgrid components with applying DR.

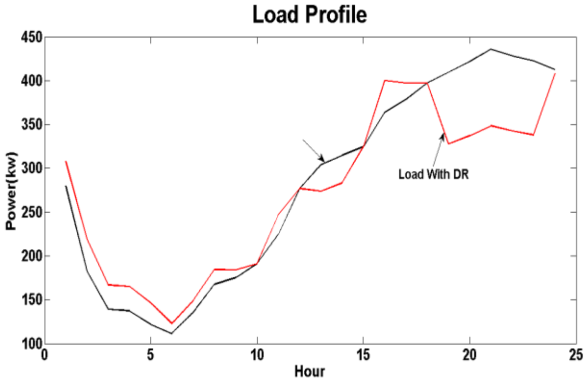

Fig. 8. Comparison of load patterns with and without applying DR.

### C. *Investigating the impacts of uncertainties on the optimal operation of microgrid*

In this section, the impacts of uncertainties such as 10% reduction in anticipated wind speed and sun irradiation on the optimal operation of microgrid will be investigated.

#### 1) *Investigating the impacts of wind speed variations on optimal operation of microgrid*

In this case, it is assumed that the wind speed is 10% less than what has been anticipated for optimal operation of the microgrid. Fig.9 shows the optimal operation results for applying unexpected wind speed variation as an uncertainty into optimization program.

The total operation cost for this case is Rials 3261576.5 (equivalent to $93.19).

Observing Fig. 9 shows that with variation and reduction in wind speed and consequently reduction in output active power of wind turbines, especially in hours in which the output power of PV arrays is zero, the amount of purchased power from the external grid is increased. Purchasing more power from external grid reduces microgrid's dependency on diesel generator; the main reason for this issue is that purchasing electricity from the external grid is a cheaper option for microgrid in compared with providing diesel (with higher cost) for its diesel generator. With applying this uncertainty, the amount of microgrid's dependency on the purchasing power from the grid increased; meanwhile, its dependency on diesel generator production is decreased.

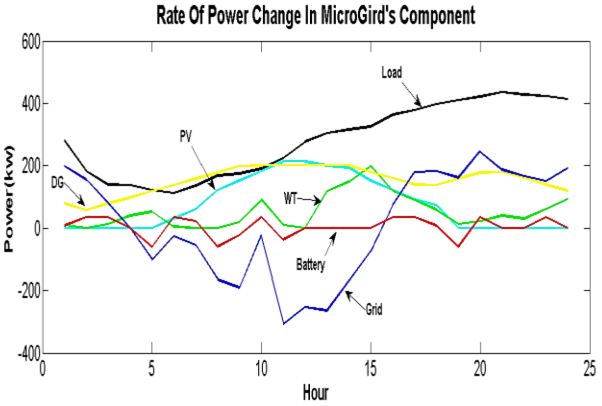

Fig. 9. Impacts of wind speed variations on the rate of power changes of microgrid components.

#### 2) *Investigating the impacts of sun irradiation variations on the optimal operation of microgrid*

In this case, it is assumed that the wind speed is 10% less than what has been anticipated for optimal operation of the microgrid. The impacts of applying this uncertainty on the active power changes of microgrid components are shown in Fig. 10.

The total operation cost for this case is Rials 3237563 (equivalent to $92.5).

Similar to the pervious subsection, as shown in Fig. 10, reduction in the output active power of PVs, the microgrid's capability in selling power to the external grid is reduced. To put it into another word, the microgrid preferred to supply its demand with diesel generator rather than purchasing power. With applying this uncertainty, the output power variation pattern of the microgrid resources, are similar to the pervious applied uncertainty (10% reduction in wind speed). But as indicated in Figs. 4 and 5, PV arrays output power are less effective in supplying microgrid demand compared to the wind turbines. Therefore uncertainty in sun irradiation has had lesser negative effects on the total operation cost of the microgrid in compared with uncertainty in wind speed.

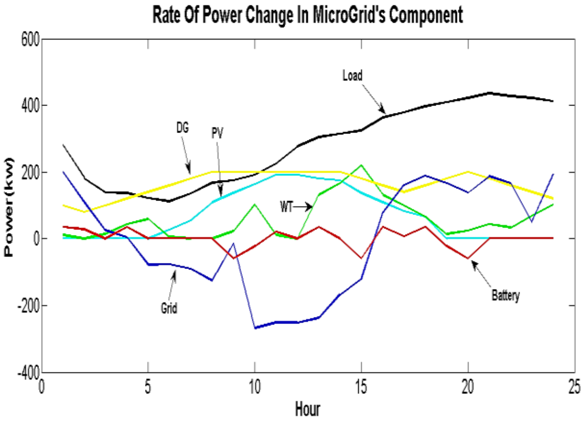

Fig. 10. Impacts of wind speed variations on the rate of owner change of microgrid components.

In Table 4, the summarized results of optimal operation of the considered microgrid with applying different strategies are presented.

Table 4. The summarized of simulation results

| Operation Mode of MG | Operation Cost ($) |
|---|---|
| Typical condition | 86.08 |
| Applying DR | 73.04 |
| 10% reduction in wind speed | 93.19 |
| 10% reduction in sun irradiation | 92.5 |

## V. CONCLUSION

In this paper, the optimal operation problem for the designed hybrid grid-connected microgrid consisted of wind turbines, PV arrays, diesel generator, power converter, and battery energy storage is investigated. Then, by applying DR, the total operation cost of microgrid is compared with typical operation.

It is shown that modification of load curve following applying DR leads to shifting demand energy from high demand peak (with higher operation cost) to the medium and low demand peak hours (lower operation cost). This issue causes increment in purchasing power demand from external grid in low and medium demand peak (with lower cost).

On the other hand, the impacts of uncertainties such as reduction in wind speed and sun irradiation on the total operation cost of microgrid is analyzed. It is shown that unexpected variation in microgrid components inputs can affect optimal operation, significantly. The amount of effects of uncertainties on the operation cost of microgrid are strongly depends the amount of being effective of the microgrid power supplier (wind turbines or PVs). In where wind turbines are more effective in supplying demand load, the unexpected reduction in wind speed can lead to higher operation cost.

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