

Multi Objective Optimal Operation of Micro Grid

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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 470.5'N and 350.59'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 irradiances 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; Micro grid; Renewable energy, Demand response; Uncertainty.*

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 footprints [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 and 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 bring about more benefits such as higher efficiency, lower 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].

The framework of DN–MG system will play important role in future power systems. Nowadays, electric power systems are undergoing significant changes; facing increasing demands for electricity such as environment friendliness, reliability improvement, energy saving and custom service [1–3].

Furthermore, the increasing use of renewable energy resources poses challenges on the future grid. To solve interconnection and control problems of various DGs, MG emerges [4]. MG is an integrated controllable system consisting of a cluster of loads, control and protection equipment's and various micro sources such as WT, PV, MT, and ESS. It pro-vides both power and heat to its local area [5,6]. Future DN can be regarded as a combination of conventional DN and MGs. As a MG offers double characteristics of generator and load and its out-put is random, operation and dispatch of DN-MG is different from that of conventional DN. And dispatch decision becomes more complex and difficult. Researches on this field should consider influence of MG output on DN operation performance. However, numerous researches are only based on MG optimal operation.

Most of them take operation cost, energy saving and emission reduction as objectives and adopt various algorithms to solve the optimal operation schemes. An economic dispatch optimization of MG considering load and DG constraints is proposed to minimize fuel cost in [7]. A low-carbon-emission MG with energy management of energy storage is presented in [8]. Ref. [9] controls the interactive power fluctuation between MG and DN by coordinating electric vehicles, ESS, and interruptible loads. Ref. [10] builds a multi-objective optimal model to achieve commercial operation of MG.

Researches above generally focus on self-interest of MG and pursue maximum

economic benefits by properly dispatching DGs and trading with DN without the consideration of power quality in DN. Several literatures take capacity constraint of PCC into consideration during operation optimizing. But the capacity constraint is just an approximate range based on tie-line power limitation with-out considering the impact of tie-line power on DN operation. As an important part of the entire grid, a grid-connected MG influences DN scheduling, such as peak-load regulation, voltage control and power flow adjustment. Suitable scheduling can enhance the stability, reliability and economy of DN; therefore it is not reasonable to only pursue MG's own economic interest and power quality. In the meantime, DN dispatch should consider operating cost of MG and its output range. MG operation optimization and DN dispatch optimization are mutually restricted and influenced. In addition, the idea of bi-level decision is practiced in power network optimization [11, 12].

This paper focuses only on the economic aspects of the micro grid 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 micro grid 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 micro grid 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 micro grid 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 micro grid are obtained from HOMER software. Then, by defining proper mathematical model and micro grid 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 micro grid with HOMER software.
- Optimal operation of hybrid grid connected micro grid 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 micro grid during a specific day.
- Studying impacts of applying demand response on the operational cost of the micro grid during a specific day)

The rest of paper is organized as follows: Section II presents a description of micro grid structure and components. In Section III, a proper mathematical model for micro grid components and their corresponding constraints are introduced to perform optimal operation on the micro grid. 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 micro grid are investigated in this section. In Section V the conclusion of this research work is given.

Under Consideration Micro Grid

The under consideration micro grid 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).

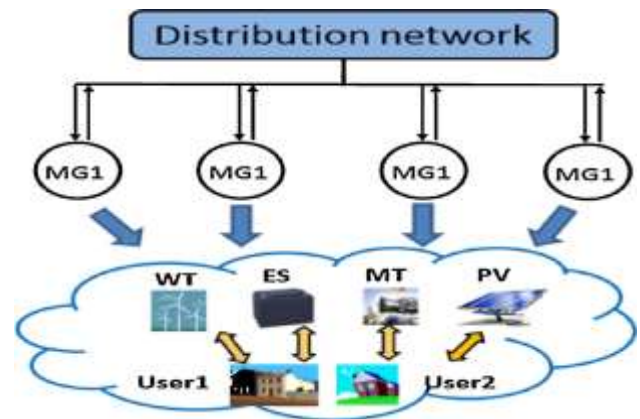


Fig. 1: New framework of distribution network

Table1: Obtained optimal sizes of micro grid components

Wind Turbin es (Kw)	PV (K w)	Diesel Generat or (Kw)	Power Convert er (Kw)	Batte ry (Kw)	Extern al Grid (Kw)
220	212.	200	100	100	330
6					

The under studying micro grid is a real rural village in which located in 350.59' N , 470.5' Kurdistan province in Iran [9]. The local load of the micro grid, 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 micro grid 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.

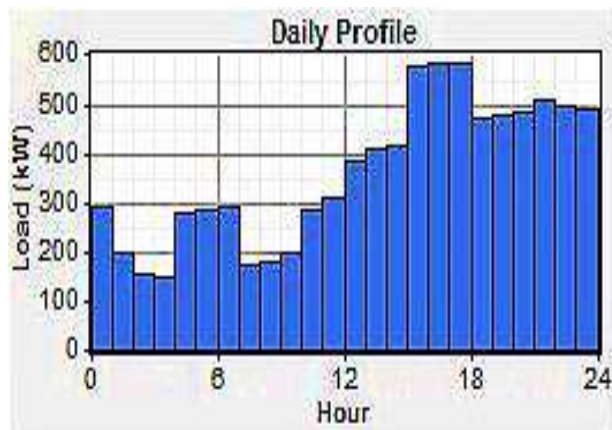


Fig. 2: Hourly electrical load profile for July month for micro grid

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 p.m. to 18 a.m
High peak	0.048	0.052	18 p.m. to 24 a.m

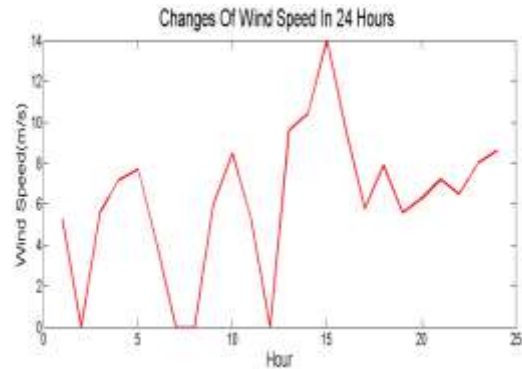


Fig. 3: Wind speed variation in the village area for 24 hours

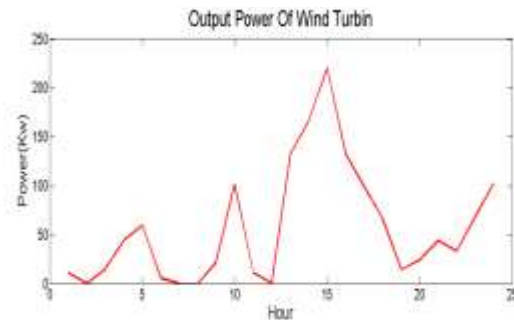


Fig. 4: Output active power variations of wind turbines for the given wind speed for 24 hours

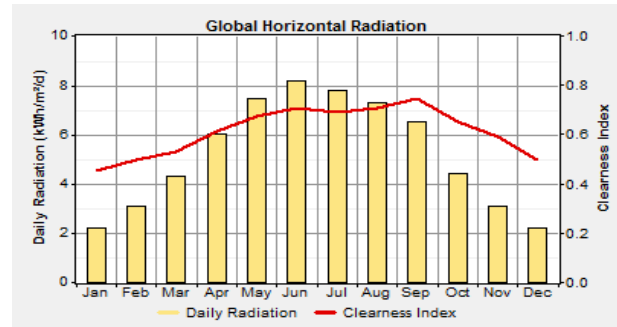


Fig. 5: Sun irradiation profile for the considered rural area

Table 3: Description of the used symbols

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

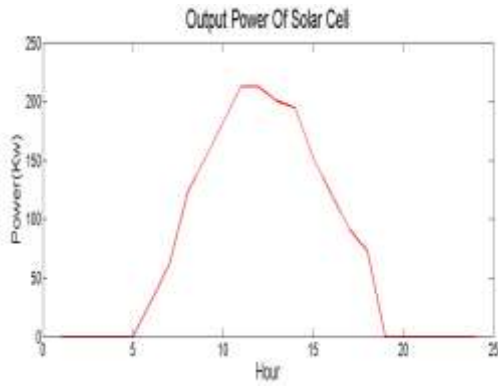


Fig. 6: Output power variations of PVs for given sun irradiation for 24 hours

Mathematical Modelling

A micro grid with functional mathematical model which is connected to a main grid must consider all constraints for the micro grid 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 micro grid 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 micro grid components including diesel generator, electricity exchange between external grid and micro grid, 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.

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 micro grid power suppliers' generation for the next 24 hours.

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

System Constraints

Power Balance Constraint

System constraints consist of power balance constraint in AC bus, and other technical

issues which are relating to the micro grid components. The AC bus constraint can be seen in equation 2.

$$\text{Power Balance Constraint} = \left\{ \begin{array}{l} P_{WT}(t) + P_{DG}(t) + P_{Gridin}(t) \dots \\ +P_{PV}(t) \times \eta_{DC/AC} + P_{dcharge} \times \eta_{AC/DC} \dots \\ P_{Gridout}(t) + P_{charghe}(t) \times \eta_{AC/DC} + P_{Load}(t) \end{array} \right\} \quad (2)$$

Grid Constraints

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

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

Diesel Generator Constraint

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

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

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.

$$\text{Battery Constraints} = \left\{ \begin{array}{l} X_{Charge}(t) + X_{Decharge}(t) \leq 1 \\ P_{Charge}(t) \leq X_{Charge}(t) \times P_{ChargeMax} \\ P_{Decharge}(t) \leq X_{Decharge}(t) \times P_{DechargeMax} \\ SOC(t+1) = SOC(t) \dots \\ + \frac{P_{Charge}(t) \times \eta_{AC/DC} + P_{Decharge}(t) \times \eta_{AC/DC}}{Battery_{Max}} \\ SOC_{Min} \leq SOC(t) \leq SOC_{Max} \end{array} \right\} \quad (5)$$

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.

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

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

Demand Response Constraint

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

$$DR = \left\{ \begin{array}{l} \sum_{t=1}^{24} DR(t) \cdot Load(t) = \sum_{t=1}^{24} Load(t) \\ 0.8 \leq DR(t) \leq 1.2 \end{array} \right\} \quad (8)$$

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 micro grid will be discussed.

Simulation Results without Applying DR

In this subsection, the optimal operation results (related to power changes of micro grid components) of micro grid which is in its normal operation mode, are indicated in Fig. 7.

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



Figure 7: Rate of power change in micro grid components during a day

As shown in Fig. 7, in the curve corresponding to the exchanged power between micro grid 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 micro grid. 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. 7, 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 micro grid 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.

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 micro grid operation profits will be increase; because, the micro grid's owners do not need to expand and install more power suppliers to meet the micro grid 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. 8, by applying the DR, the micro grid capability for selling power to the external grid is decreased. Consequently, the micro grid 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. 9, the modified load curve (considering DR in optimization program) is compared with the normal load curve. As expected, the total micro grid 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. 9, 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 micro grid operators and costumers.

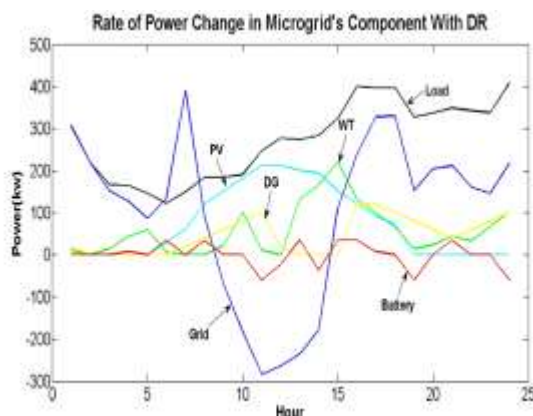


Fig. 8: Rate of power changes in micro grid components with applying DR

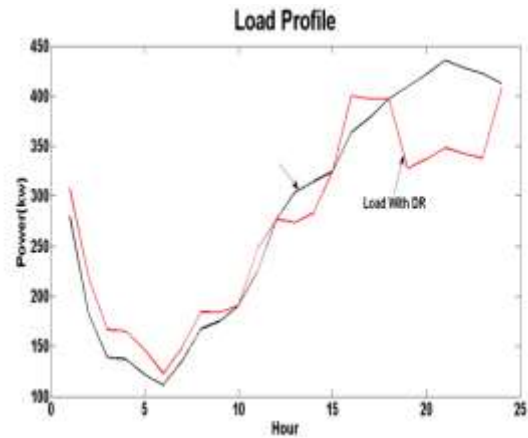


Fig. 9: Comparison of load patterns with and without applying DR

Investigating the Impacts of Uncertainties on the Optimal Operation of Micro Grid

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

Investigating the Impacts of Wind Speed Variations on Optimal Operation of Micro Grid

In this case, it is assumed that the wind speed is 10% less than what has been anticipated for optimal operation of the micro grid. Fig.10 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. 10 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 micro grid's dependency on diesel generator; the main reason for this issue is that purchasing electricity from the external grid is a cheaper option for micro grid in compared with providing diesel (with higher cost) for its diesel generator. With applying this uncertainty, the amount of micro grid's dependency on the purchasing power from the grid increased; meanwhile, its

dependency on diesel generator production is decreased.

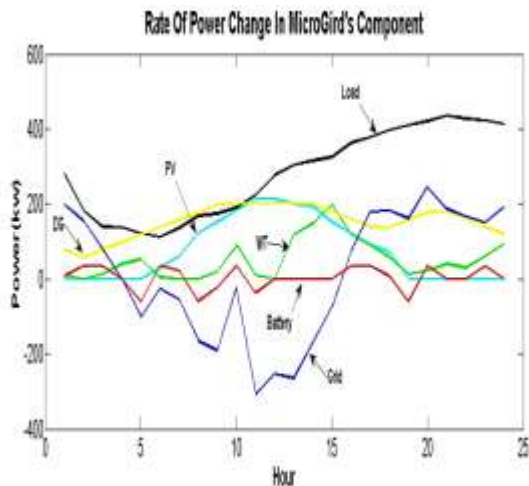


Fig. 10: Impacts of wind speed variations on the rate of power changes of micro grid components

Investigating the Impacts of Sun Irradiation Variations on the Optimal Operation of Micro grid

In this case, it is assumed that the wind speed is 10% less than what has been anticipated for optimal operation of the micro grid. The impacts of applying this uncertainty on the active power changes of micro grid components are shown in Fig. 11.

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 micro grid's capability in selling power to the external grid is reduced. To put it into another word, the micro grid preferred to supply its demand with diesel generator rather than purchasing power.

With applying this uncertainty, the output power variation pattern of the micro grid resources, are similar to the pervious applied uncertainty (10% reduction in wind speed). But as indicated in Figs. 5 and 6, PV arrays output power are less effective in supplying micro grid demand compared to the wind turbines. Therefore uncertainty in sun irradiation has had lesser negative effects on the total operation cost of the micro grid in compared with uncertainty in wind speed.

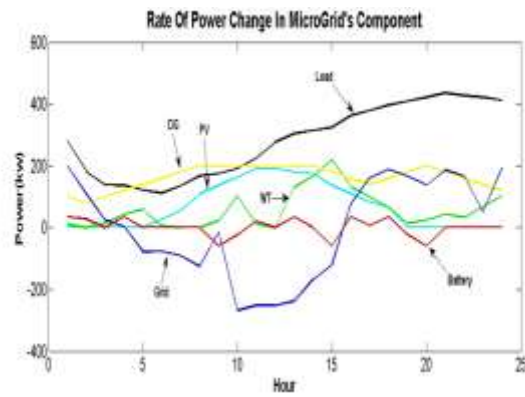


Fig. 11: Impacts of wind speed variations on the rate of owner change of micro grid components

In Table 4, the summarized results of optimal operation of the considered micro grid 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

Conclusion

In this paper, the optimal operation problem for the designed hybrid grid-connected micro grid 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 micro grid 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 micro grid is analyzed. It is shown that unexpected variation in micro grid components inputs can affect optimal operation, significantly. The amount of effects of uncertainties on the operation cost

of micro grid are strongly depends the amount of being effective of the micro grid 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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