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Review Article

OPTIMAL SIZING OF ENERGY STORAGE IN ORDER TO IMPROVE MICROGRIDS RELIABILITY USING CONTINGENCY PLANNING

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ABSTRACT
In this paper, a method to determine the optimal size of energy storage in a microgrid system enhancing the reliability is presented. The proposed method is based on a probability model and all possible terms for microgrid operation are considered. In this regard, the standalone and then the grid-connected mode are investigated. To solve the problem, mixed integer linear programming (MILP) with the aim of minimizing the storage system installation and operating costs and also increasing profitability of grid-connected microgrid is utilized. The results show that installing optimal capacity of energy storage in a microgrid improves the reliability. Moreover, it reduces operating costs and increases profitability of grid-connected microgrid compensating the lack of wind and solar power as well as supplying load demand.

Keywords: *Energy Storage, Optimal Sizing, Microgrid, Reliability, Distributed Generation*

INTRODUCTION
Today, with development of energy technologies, rising attention to environmental issues and the importance of improving the electrical networks reliability, the incentive to produce renewable energy in distribution system is provided (Hafez and Bhattacharya, 2012). However, connection of distributed generation resources to current distribution systems has not fulfilled technical and economic needs of investors. Although it was expected that increasing penetration of distributed generation resources would improve power quality, due to power fluctuations caused by the voltage and frequency difference of various renewable energy sources, opposite results have been achieved. Using distributed energy resources can reduce the need to extend traditional electrical grids potentially, however, controlling such resources leads to a new challenge in operation of a reliable and economical grid. This problem is addressed partially by microgrids with decrease of responsibility to control the grid achieving maximum economic efficiency. As a result, the proper solution is utilizing small microgrids which are independent of the main grid or other microgrids (Hatziargyriou *et al.*, 2007).
Microgrid is defined as a set of loads, distributed energy resources and energy storage system that can act as a controllable load, generator and totally a controllable system to produce power and heat for a local area. From the consumer's side, microgrid is like a separate and autonomous system that meets the needs, ranging from energy, power quality to reliability. But from the power system side, the microgrid is seen as a producing member or a load (Palizban *et al.*, 2014). From the beginning of using microgrid in distribution systems, various models and structures have been proposed for it. In primary models, basic structure, energy management and control issues have been discussed (Lasseter and Paigi, 2004). Optimal management, planning and performance models of microgrid have been studied with the completion of microgrid concept and distributed energy resources.
Due to the uncertainty in output power of distributed generation resources such as wind and solar, microgrid user would have different problems in purchasing power from these units. But using the storage can give a fairly accurate estimate of the output of these resources and reduce margin of error for user. Also, using renewable resources increases voltage and frequency fluctuations, causing an imbalance between production and consumption. As a result these units need batteries and must be supported by fossil fuel resources or more expensive sources as fuel cell (Etxeberria *et al.*, 2010). For example, for a penetration rate of 10% for wind units, required balancing power to be provided through other traditional

producing sources is equal to 2-4% of the total production capacity of the wind units (Patrao *et al.*, 2015). Another reason to use energy storage for microgrid while using renewable resources is that the production capacity of these units in some hours for example wind units at midnight and solar units at noon provide energy more than required load demand in microgrid (Benysek *et al.*, 2011). Therefore, utilizing energy storage in microgrid and determining its optimal capacity is crucial.

MATERIALS AND METHODS

In this paper, a method to determine the optimal size of energy storage in a microgrid system with the aim of enhancing the reliability is presented. In next sections firstly, the problem is modeled considering all possible operation terms for microgrid and then the algorithm applied to solve the optimization problem is introduced. Two modes for microgrid are investigated in case study section: standalone and grid-connected. To solve the optimization problem, mixed integer linear programming is used to minimize the storage system installation and operating costs of independent microgrid simultaneously and also to improve the profitability of grid-connected microgrid. Finally, conclusions are given in last section.

RESULTS AND DESICUSSION

Problem Modeling

To model the problem, two scenarios are analyzed: stand alone and grid connected microgrid. In first scenario, the objective function for independent microgrid is the total cost of microgrid in daily utilization consisting of total operation cost (TUCC) and battery cost (TCPD) on a daily basis, which must be minimized as following:

$$TC = TCPD + TUCC \tag{1}$$

For the second scenario, objective function of optimization related to grid connected microgrid is defined according to equation (2) and is aimed at maximizing the profitability of the microgrid. To achieve this purpose, the benefit from the sale of power to the main grid (MB) is subtracted from microgrid total cost:

$$TB = MB - TC \tag{2}$$

microgrid utilization cost is including fuel consumption in fossil fuel units such as microturbine and fuel cell, operation and maintenance costs and units starting up costs. It has to be mentioned that investment and operation costs of storage are defined separately. So the total cost function for utilization of productive resources related to microgrid TUCC is defined as follows:

$$TUCC = \sum_{t}\sum_{n\in CG} RC\left(P_{t,n}\right) + SC\left(P_{t,n}\right) + C\left(P_{t,n}\right) + \sum_{t}\sum_{n\in WG} WOC\left(P_{t,n}\right) + \sum_{t}\sum_{n\in PG} PVOC\left(P_{t,n}\right) \tag{3}$$

Where, CG is the number of dispatchable sources, WG and PG are the number of wind turbines and photovoltaic resources in microgrid, respectively. t indicates the hours in a day (study duration) and n is defined as total number of distributed energy resources in microgrid. Operating costs of fossil fuel units are $RC(P_{t,n})$, $SC(P_{t,n})$ and $C(P_{t,n})$ that indicate the cost of spinning reserve services in microgrid, starting up and down costs of units as well as maintenance costs, respectively.

Given the uncertainty of production capacity and load forecast in microgrid, dispatchable units should participate in providing spinning reserve. As a result a cost due to readiness to provide spinning reserve is considered in planning of the microgrid and is calculated according to equation (4):

$$RC\left(P_{t,n}\right) = r_n R_{tn} \tag{4}$$

In above equation r_n is the factor of spinning reserve cost for unit n and R_{tn} is the presentable power by unit n at hour t.

For dispatchable units in each phase of starting up and down, one cost is defined and added to the microgrid operation cost per hour. The cost is calculated using equation (5):

$$SC\left(P_{tn}\right) = d_n DU_{tn} + s_n SU_{tn} \tag{5}$$

In above equation d_n is the considered cost start down unit and DU_{tn} is a binary variable representing the status change of unit n from on to off. s_n is the cost for unit starting up and SU_{tn} indicates binary variable that represents the status change of unit n from off to on at hour t, respectively.

Operation cost for unit i is defined in (6):

$$C_t\left(P_i\right)=a_i+b_i P_{t,i} \tag{6}$$

In above equation a_i, b_i, $P_{t,i}$ and $C_t(P_i)$ are the fixed cost factor, variable cost factor, produced power and operation cost for unit i at hour t (Chen *et al.*, 2012).
WOC (P_{tn}) and PVOC (P_{tn}) are the operation and maintenance cost of wind turbines and solar cells. WOC (P_{tn}) at any time is proportional to the production capacity (Nilsson and Bertling, 2007) and is defined according to equation (7):

$$WOC\left(P_{tn}\right)=U_{t,n}P_{tn}c_{\omega} \tag{7}$$

In above equation c_ω, P_{tn} and $U_{t,n}$ are the factor of wind turbine cost, produced power and binary variable indicating dispatch status, respectively at the hour t. Operation and maintenance cost of solar cells is defined similarly, using equation (8):

$$PVOC\left(P_{tn}\right)=U_{t,n}P_{tn}c_{pv} \tag{8}$$

Where, c_{pv} is the factor of solar cells cost and $U_{t,n}$ identifies binary variable indicating the status of solar cells in microgrid planning (Diaf *et al.*, 2008).
Benefit from the power exchange with the main grid is modeled in equation (9), which represents total produced power sale to microgrid or main grid consumers per hour.

$$MB=\sum_t MP_t \sum_{n\in CG} P_{t,n} \tag{9}$$

Where, MP_t is electricity price per hour.
Investment cost for installation of energy storage system depends on the maximum power transferable and maximum energy savable in energy storage system. So the cost of investment using equation (10) is calculated:

$$C_{ESS}=C_P P_{Emax}+C_W W_{Emax} \tag{10}$$

Where, P_{Emax} (kw) is maximum power and W_{Emax} (kwh) is the maximum energy and C_P and C_w are factors related to them.
The annualized cost of investing in energy storage system using equation (11) is defined:

$$AOTC=\frac{r\left(1+r\right)^l}{\left(1+r\right)^l-1}\times C_{ESS} \tag{11}$$

Where, r is interest rate equal to 6% and *l* indicates the battery life.
Operation and maintenance cost of the energy storage system consists of two parts. First one is constant and depends on nominal power of storage system and second is related to energy depleted from it. Equation (12) represents this relationship:

$$C_{OM}=C_{Mf}P_{Emax}+C_{Mv}W_{Emax} \tag{12}$$

C_{Mf} ($ / kw) and C_{Mv} ($ / kwh) are defined as fixed and variable costs of storage. The total annual cost of storage is calculated adding equations (11) and (12) and it is normalized on a daily basis according to equation (13):

$$TCPD=\frac{1}{365}\left(AOTC+C_{OM}\right) \tag{13}$$

Problem constraints including the balance of power, limitations related to distributed energy resources and battery must be satisfied. These constraints should be considered in all scenarios and conditions as described in following.

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Total produced power by sources such as microturbines, fuel cell, wind turbine, solar cells and existing power of battery must supply load demands.
Moreover, while the microgrid is connected to main grid, transferred power between them would be available. The balance between production and consumption is represented using equation (14):

$$\sum_{n\in CG} P_{tn} + \sum_{n\in WG} P_{tnt} + \sum_{n\in PG} P_{tn} + \sum_{n\in ES} P_{tn} = \sum_{i} PD_{ti} + PL_t \tag{14}$$

Where, ES is the number of batteries, PD_{ti} is the load value relevant to bus i, P_{tn} is produced power of source n and PL_t is microgrid loss at hour t. In proposed solution model, loss is ignored because of its small value. Charge and discharge equations of energy storage are shown in (15) to (21). $P_t^{E,\,d}$ is discharged power of battery bank during the time t and $P_t^{E,\,c}$ is injected power from grid to it. C(t) is the energy stored in battery bank at time t, and Δt is the time interval. η_d and η_c are discharge and charge efficiency, respectively. W_h is internal discharging energy of battery banks (depending on battery type) during the idle mode.

$$C(t+1) = C(t) - \Delta t P_t^{E,d} / \eta_d \tag{15}$$

$$C(t+1) = C(t) + \Delta t P_t^{E,c} \eta_c \tag{16}$$

$$C(t+1) = C(t) - W_h \tag{17}$$

$$0 \le P_t^{E,d} \le P_E^{d,max} \tag{18}$$

$$0 \le P_t^{E,c} \le P_E^{c,max} \tag{19}$$

$$C_{min} \le C(t) \le C_{max} \tag{20}$$

$$C(0) = C(T) = C_{in} \tag{21}$$

$P_E^{d,\,max}$ is maximum power delivered to the grid by battery and $P_E^{c,\,max}$ is the maximum power of battery in charging mode that are limited according to equations (22) and (23).

$$P_E^{d,max} \le \min\left(\eta_d\left(C_{max} - C_{min}\right),\ \eta_d K_E C_{max}\right) \tag{22}$$

$$P_E^{c,max} \le min((C_{\max} - C_{\min})/\eta_c, (K_E \times C_{\max})/\eta_c) \tag{23}$$

K_E is the factor of battery power that is dependent on battery type and its structure. K_E is considered as depth of battery discharge in both charge and discharge mode (Manwell and McGowan, 1993).
Spinning capacity available in each unit is limited according to (24):

$$R_{tn} \le \min\left(R10_n \times U_{t,n}, P_n^{max} \times U_{t,n} - P_{tn}\right) \tag{24}$$

Where, $R10_n$ is 10 minute reserve capacity of unit n and $U_{t,n}$ is binary variable indicating the unit status.
The minimum required spinning reserve for the generator with highest power in system at any hour is indicated in (25):

$$CR_t \ge P_n \tag{25}$$

Spinning reserve constraint for system considering uncertainty in every hour is limited according to (26):

$$\sum_{n\in CG} R_{tn} + \sum_{n\in ES} \min\left(\eta_d\left(C_{n,t} - C_{min}\right), \left(P_E^{d,max} - P_{ESt}\right)\right) \ge +RMSE \sum_{n\in WG} P_{tn} + MAPE \sum_{n\in PG} P_{tn} + \kappa \sum_{i} PD_{ti} + \omega \times CR_t \tag{26}$$

The output power of each DG resource should be limited to the minimum and maximum power of units. This constraint is defined in (27):

$$U_{t,n} P_n^{min} \le P_{tn} \le U_{t,n} P_n^{maxn} \tag{27}$$

The limitation related to minimum on and off time for dispatchable units is represented in (28) and (29):

$$\left(US_{t-1,n} - UT_n\right)\left(U_{t-1,n} - U_{t,n}\right) \ge 0 \tag{28}$$

$$\left(US_{t-1,n} - DT_n\right)\left(U_{t,n} - U_{t-1,n}\right) \geq 0 \qquad (29)$$

Optimization Algorithm

Implementation of the proposed algorithm in this paper to solve the discussed model is as follows:

- Wind turbine and solar cell output power are calculated.
- According to data obtained, minimum and maximum battery capacities are computed.
- Parameters and constraints with respect to the microgrid and battery type setting are set.
- The size of battery for the implementation of first plan will be set equal to minimum.
- Optimal and economic programming of the units is performed and results would be recorded.
- Battery capacity changes with definite steps and optimized planning continues until the battery capacity reaches to the maximum value.
- The results would be compared with each other and then the best planning and its corresponding optimal battery capacity and power are obtained.

Case Study

In this section the optimal sizing of storage capacity for microgrid is analyzed considering two scenarios. Data related to wind speed, solar radiation, microgrid load demand and also hourly price of electricity have been shown in figure 1 (Wang and Gooi, 2011). Required information about units cost functions, the cost of starting up, constraints on maximum and minimum produced power of units, production increase rate, the minimum off and on time and units interval rate are shown in table 1 (Tsikalakis and Hatziargyriou, 2011). Wind turbine and solar cell cost factor are 0.06 $/Kw and 0.15 $/kw, respectively. Furthermore, energy storage data in table 2 is given (Ning and Popov, 2004).

Table 1: Distributed energy resources data

FC	MT2	MT1	
0.5	0.35	0.13	b ($\$/kW$)
80	50	30	a ($)
0.01	0.01	0.01	r_n ($)
100	100	100	P_n^{min} (kW)
1000	1000	2000	P_n^{max} (kW)
0	0	2	UT_n (h)
0	0	2	DT_n (h)
-1	-1	2	US_{0n} (h)

Table 2: Energy storage data

0	C_P ($\$/kw$)
600	C_w ($\$/kwh$)
0	C_{Mf} ($\$/kw$)
20	C_{Mv} ($\$/kwh$)
90	Charging efficiency
90	Discharging efficiency
60	Depth of discharge
3	Life time (year)

Scenario One: Independent Microgrid

Total operation cost of independent microgrid for different energy storage capacity values is shown in figure 2. Optimal energy storage capacity, maximum power limit and total operation cost (TC) are 1200 kwh, 600 kwh and $7258, respectively. In the absence of battery storage, units operating cost (TUCC) will be equal to $8016 which would have a $758 decrease in case of using energy storage. Also, battery daily cost is $800. For capacities higher than 2000 kwh, operating cost (TUCC) will not change and just battery daily cost is increased.

Production planning of dispatchable units in both absence and presence of energy storage is shown in figures 3 and 4. According to the load profile, peak values are occurred at hours 13 and 17. During the microgrid planning without the presence of energy storage, microturbine 2 is put in system at different hours with minimum power to satisfy spinning reserve constraints and to supply load demand.

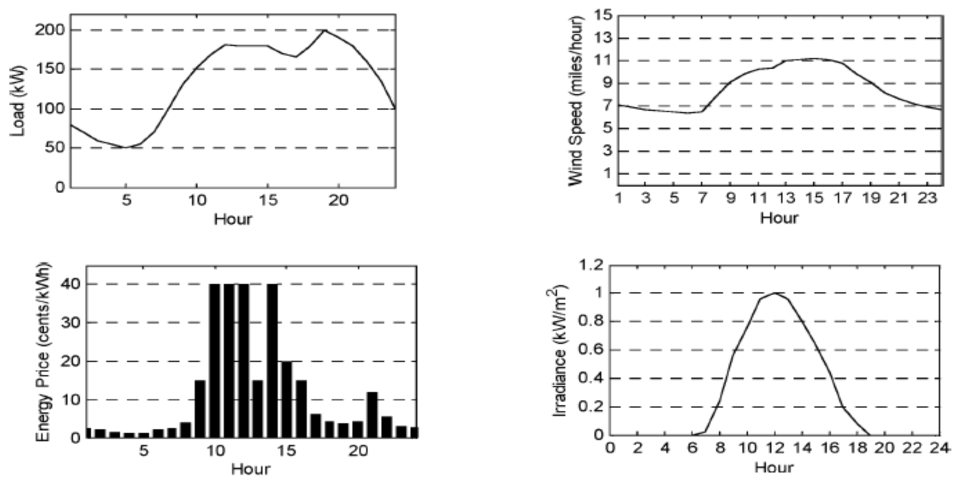

Figure 1: Hourly wind speed of WT and irradiance of PV, load profile and energy price in system

Also at the hour 17 as load peak in the evening, due to decline in production of wind turbine and solar cells, the produced power of two microturbines is not enough to meet the needs of microgrid and thus fuel cell is put in system at the hour 17. Using fuel cell with minimum power at hour 13 is to satisfy the limits of spinning reserve with microturbine 2 and to supply the remaining load demand at that hour.

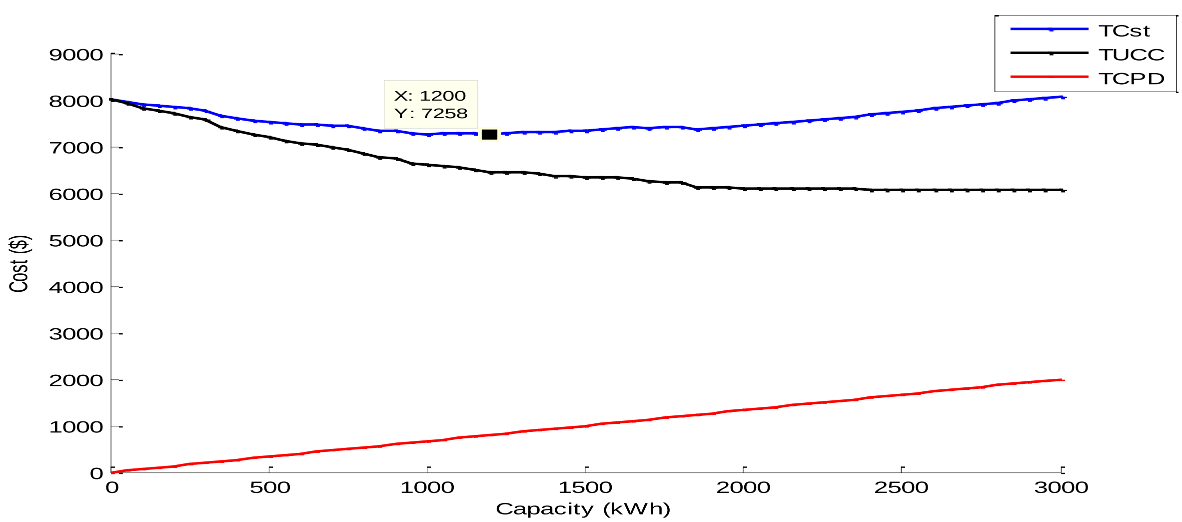

Figure 2: Daily operation cost of standalone microgrid

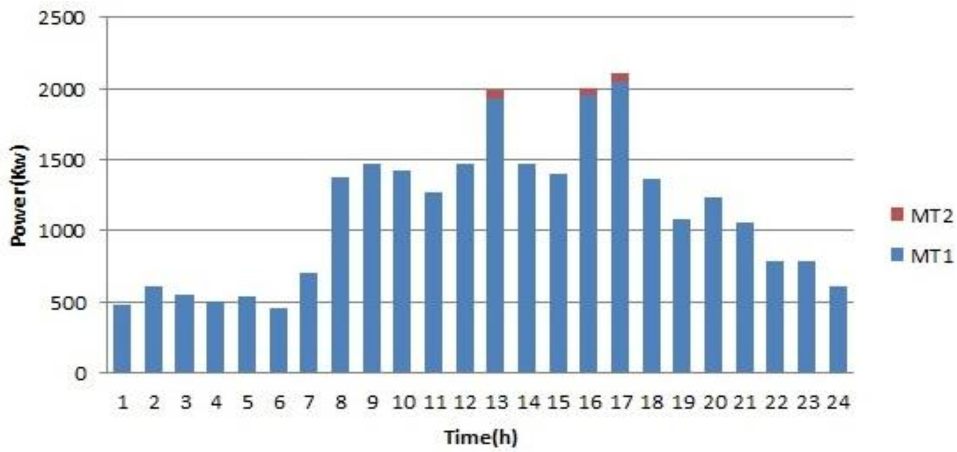

Figure 3: Dispatchable units planning with presence of energy storage

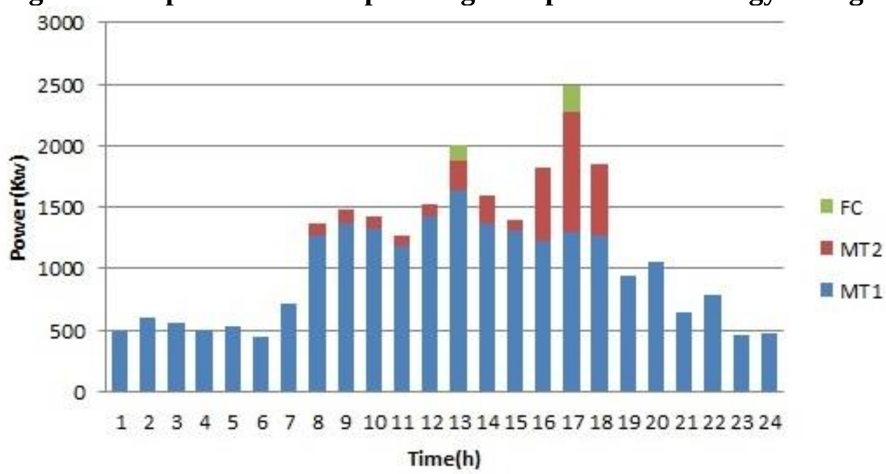

Figure 4: Dispatchable units planning without presence of energy storage

The Second Scenario: Connected Microgrid

Unlike the previous scenario that aims to reduce the operating costs of microgrid in the presence of battery, in this section the goal is defined to increase microgrid profitability. Figure 5 shows the benefit obtained from planning for grid connected microgrid in terms of energy storage capacity. The profit without using the battery is $10139 and optimal energy storage capacity is 550kwh where maximum power limit is 275kw, resulting a profit of $10310 for microgrid.

Planning of microgrid without energy storage is shown in figure 6. Because at some hours, production cost in microgrid is more than purchase cost from the grid, energy must be purchased at the hours when the electricity is cheap. However, due to the uncertainty in the production of renewable units and loads that are considered in spinning reserve, microturbine 1 is not allowed to be off and it is put in system with minimum power. At the hours when electricity is expensive, microgrid is to provide required spinning reserve by microturbine 2 to sell low cost energy produced by renewable sources and microturbine 1 to the grid. Because the cost of microturbine 2 to be on is more than purchasing energy at the hour 8, the reserve capacity is provided by microturbine 1 and required power is purchased. This process is to reduce costs and to achieve profitability in the microgrid. Resources planning in presence of storage are shown in figure 7. At the hour 7 the load is supplied by microturbine 1 and renewable sources but because energy storage can satisfy spinning reserve constraints, all units except microturbine 1 are off at the time of low cost energy and power is purchased from the main grid. When energy is expensive, microturbine 1 is put in system with maximum power to supply the load and also energy is sold to the grid.

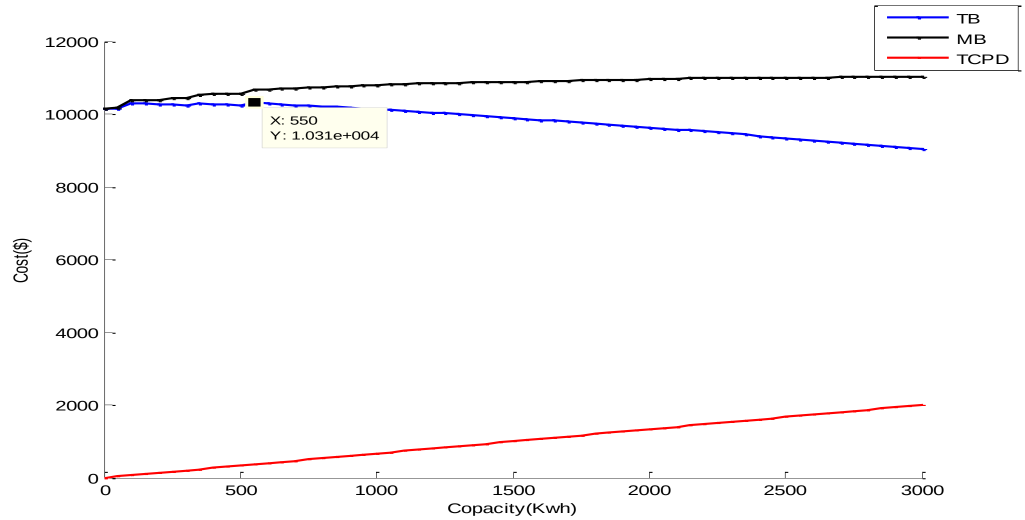

Figure 5: Daily profit of grid-connected microgrid operation

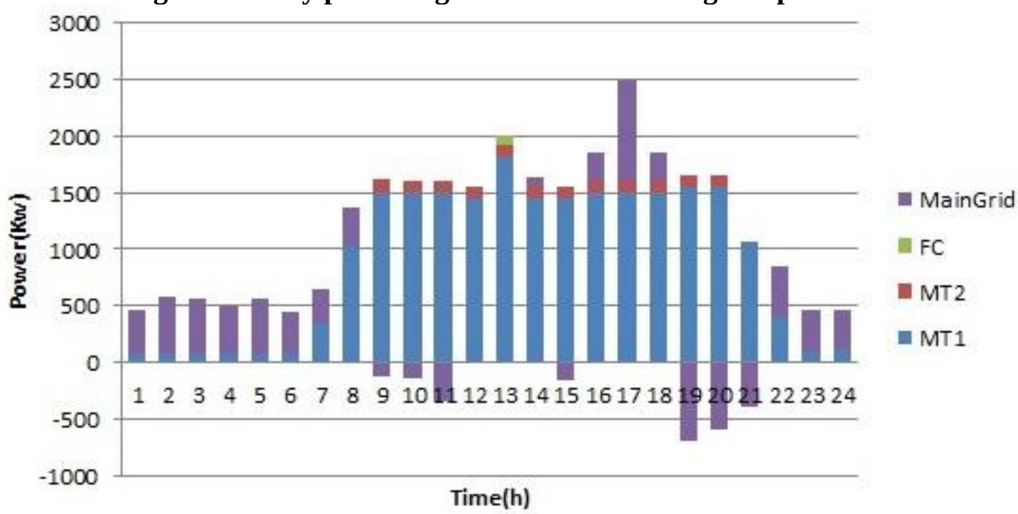

Figure 6: Dispatchable units planning without presence of energy storage

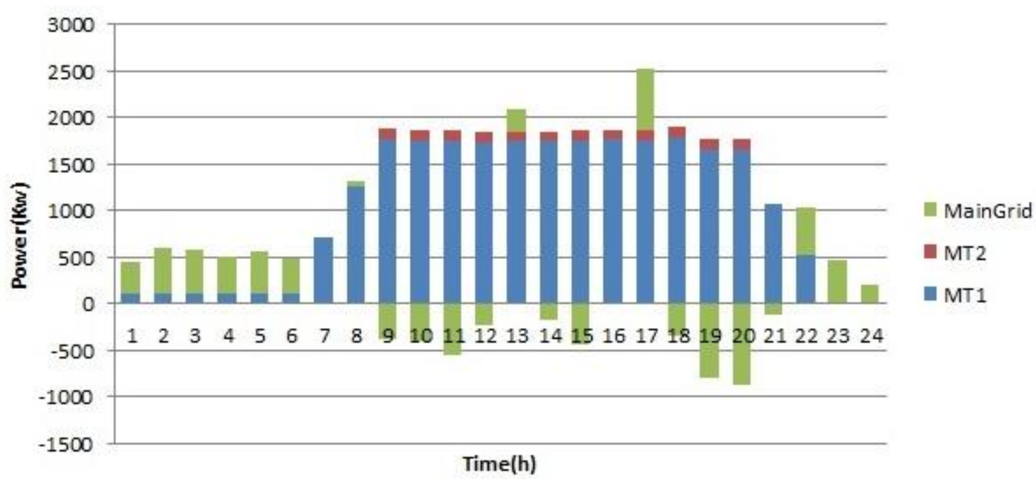

Figure 7: Dispatchable units planning with presence of energy storage

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CONCLUSION

This study was conducted to determine the optimal size of energy storage in a microgrid with the purpose of enhancing the reliability. The proposed method is based on a probability model considering all possible terms for microgrid operation. Microgrid is analyzed in two scenarios, the standalone and grid connected mode. Results showed that in standalone micro grid with regard to the participation of energy storage in satisfying spinning reserve constraints without any cost, the battery performance is related to spinning reserve limits and less involved in supplying loads. From the standpoint of determining the optimum capacity, this behavior means the direct and high effect of microgrid spinning reserve capacity in selecting the optimal storage battery. Furthermore, the battery capacity in grid connected microgrid is decreased by adding the possibility of energy purchasing and selling. This amount is adequate to cover a large part of spinning reserve capacity and to inject power at the hours when the energy price is high causing expensive energy sources to stay off.

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