Dynamic Economic Dispatch on Micro Grid Electrical Systems Using Quadratic Programming

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Abstract—**Currently the needs of electric power increased rapidly along with the development of technology. The increase in power requirements is contrary to the availability of sources of energy depletion of oil and coal. This problem affects the national electrical resistance. To meet the needs of large electric power with wide area coverage is required small scale distributed power generation. This distributed generation (DG) of renewable energy sources sought to minimize the use of energy resources such as oil and coal and connected to the micro grid and use the battery as a power balance. Because of there are many DGs and the use of batteries, therefore it is important to determine the optimal power generation of each plant as well as the use of battery based on the optimal capacity so that requirement of electric power can be met with minimal cost each time. This optimization is known as Dynamic Economic Dispatch. In this study, the methods of Quadratic Programming is required to solve the optimization problem.**

Keyword— micro grid, Dynamic Economic Dispatch, Quadratic Programming, Battery, Energy Storage

I.   INTRODUCTION

Electric power is one requirement that is essential in human life. Electric power demand is growing causes electrical power to be supplied by the generator becomes very large. Renewable energy sources as well as economically is a decisive factor of industrial development that could improve people's living standards. Since the industrial revolution, the need for electric energy increased sharply [1]. As good form in generating a great power with wide area coverage, the generation system spread becomes important to meet the load demand, increase reliability, and so on [2,3]. *Economic dispatch* (ED) is important in the control and operation of power system [4]. The main function of the ED is to schedule the generation of any plants that operate to meet the needs of the load on the generation cost at least [5].

Beside from the cost of operation, a very important factor to be analyzed is the use of the battery as a power balance. Battery can be used in certain circumstances to provide electrical power in certain conditions. However the constraint limitations of energy stored in the battery can also limit the performance in supplying of electric power at a certain point [6]. Therefore, it is important to determine the optimal capacity of battery connected to micro grid system.

Dynamic Economic Dispatch (DED) is an optimization method for determining the optimum generation with minimum generation cost in every hour each continuously.

The main idea of DED was a developed from conventional economic dispatch. Therefore, such kind of these method need Quadratic Programming because very simple and effective approach to find a global solution [7].

II.   SYSTEM DESCRIPTION

A. Micro Grid Electrical Systems

Micro Grid is a small system with consist of thermal generators such as diesel generators, micro turbines and fuel cells as well as renewable energy power sources such as photovoltaic, wind turbine and battery. Micro grid is made from small-scale DGs and are implemented close to the load to increase system reliability and minimize losses. The system used in this study is the system with the type of islanded operation. With this type of operation, the electric power from PLN are not used. Some electrical energy sources modeled in micro grid system are wind turbine, photovoltaics, fuel cells, micro turbines, diesel generators and batteries.
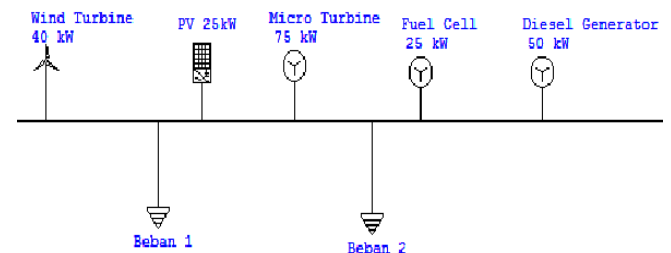

Figure 1. Micro grid operation in islanded mode.

B. Dynamic Economic Dispatch

Dynamic economic dispatch is the division of power that must be generated by the generator in an electric power system to meet load requirements at minimum cost. A large load on a power system is always changing every certain period of time. Therefore, to supply the load economically in each period of time-*t* for each *h*-unit generator, calculation of optimization based dynamic economic dispatch is done.

At the micro-grid system, dynamic economic dispatch is carried out to determine the optimum power generation from thermal generation (fuel cell, micro turbine and diesel generator) as well as the use of power from battery at every time period to achieve generation cost minimally.

Determination of power generation in each generator can only be varied at the) specific limits (constraints). Cost function of *H*-unit a generator in the time period *t* is modeled by the equation:

$$CF_{ht} = a_{ht}P_{ht}^2 + b_{ht}P_{ht} + c_{ht} \qquad (1)$$

Where:

CF_{ht}	: Total operating cost thermal generator (€ / h)
a, b, and c	: coefficient of thermal generator costs
P_{ht}	: Power generated at the plant h the time period t (kW)

The relations of generated power by the power plant is not linear to the generation cost, the combination of the generated output power by each *h*-unit of generator with time period of *t* at power plant systems must be able to meet the power requirements of the electric power system *(*equality constraint) and meet the minimum and maximum limits of the power generated by the generator (inequality constraints). Because the problem is complex, then for solving the problems can be done by the method of iteration, the parameters on the parameters described can be written in the equation:

$$CF_{ht} = \sum_{t=1}^{T}\left(\sum_{h=1}^{n}(a_{ht}P_{ht}^2 + b_{ht}P_{ht} + c_{ht})\right)$$

Where:

CF_{ht}	: Total operating cost of thermal generator (€ / h)
a, b, and c	: coefficient of thermal generator costs
P_{ht}	: H generator power generated in the time period *t* (kW)

$P_{FC}\ min \leq P_{FC} \leq P_{FC}\ max$
$P_{MT}\ min \leq P_{MT} \leq P_{MT}\ max$
$P_{DG}\ min \leq P_{DG}\ P \leq_{DG}\ max$
$P_{charge}min \leq P_{batt} \leq P_{charge}max$

Where:

$P_{FC}\ min$	: minimum operation power of the fuel cell
$P_{FC}\ max$	: maximum operation power of the fuel cell
$P_{MT}min$	: minimum operating power of micro turbine
$P_{MT}max$	: maximum operating power of a micro turbine
$P_{DG}min$	: minimum operation power of diesel generators
$P_{DG}max$	: maximum operation power of the diesel generator
$P_{charge}min$	: minimum operating power of battery
$P_{charge}max$	: operating power of battery

$P_{FC}\ min$	= 5 kW
$P_{FC}\ max$	= 25 kW
$P_{MT}\ min$	= 5 kW
$P_{MT}\ max$	= 75 kW
$P_{DG}\ min$	= 2 kW
$P_{DG}\ max$	= 6 kW
$P_{charge}min$	= 0 kW
$P_{charge}max$	= 30 kW

Of all the power plants that exist on the system, there are three plants that require fuel to operate. The power plant is a fuel cell, micro turbine and diesel generators. Fuel cell and micro turbine using natural gas as fuel and diesel generators use diesel fuel. Large costs on thermal plants in addition influenced by the characteristics of the engine is also affected by the cost of fuel, therefore the three power plants have different characteristics.

Besides the three power plants discribed above, there is battery that will need generation cost, where the cost is calculated based on the cost of purchase and maintenance of battery described in equation battery. The function of the total operating costs of the plant are as follows:

$$CF(P) = CF(P_{FC}) + CF(P_{MT}) + CF(P_{DG}) + CF(Pbatt) \quad (3)$$

Where:

CF (P)	: total operating costs of plants that have the generation cost in € / h
CF (PFC)	: the total cost of operating the fuel cell in € / h
CF (PMT)	: total operating costs *of* micro turbine in € / h
CF (PDG)	: total cost operating diesel generator in € / h
CF (Pbatt)	: total operating costs *of* battery in € / h

C. Quadratic Programming in Micro Grid System

Model of linear programming is a model that is very reliable to use in the analysis of the problems of science, industry, *engineering,* and business. However, this model has its limitations because not all the problems are linear. In addition, the linear model only gives the best results on the problem with the first order. The model is one level above the model is quadratic programming where able to solve the problems of nonlinear and model it into an objective function. Quadratic programming is one of the optimization methods which are specifically used to optimize (minimize or maximize) the problem issues quadratic function of several variables that depend on linear constraints on variables specified. Quadratic programming can be modeled in a following equation:

$$F(x) = f + c^T x + \frac{1}{2}x^T Hx \qquad (4)$$

In accordance with the constraint of linear system
$lb \leq Ax \leq ub$
$x_{min} \leq x \leq x_{max}$

Where:

F	= constant scalar
c	= constant matrix of n-vector
H	= nxn matrix
A	= matrix of mxn
ub, lb	= constant m-vector
x	= n-vector of unknown

III. SYSTEM MODELING

The microgrid model performed in this research is a system of radial distribution. The system is supplied by a diesel generator 50 kW, fuel cell 25 kW, micro turbine 75 kW, wind turbine 40 kW, photovoltaic 25 kW and supported by 300 kWh of batteries.
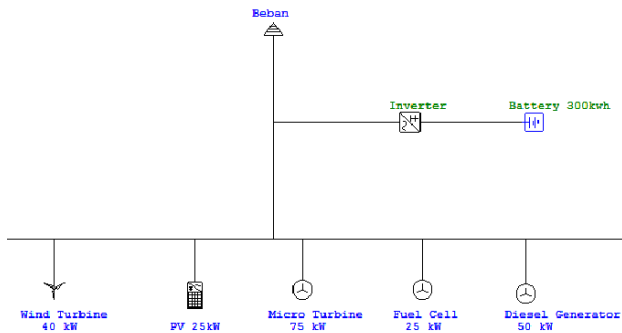
Figure 2. The micro-grid electricity system

D. Photovoltaic

The characteristics of photovoltaic is tested in a standard condition (1000 W/m² and 25°C) to generate the power corresponding to its rating. The output power of photovoltaic can be calculated by the equation:

$$P_{PV}=M\{P_{STC}\frac{G_{ING}}{G_{STC}}(1+k(T_c-T_r)) \qquad (5)$$

Where:
P_{PV} : The power output of the current module in W
P_{STC} : STC modules at maximum power in W
G_{ING} : Actual radiation in W/m²
G_{STC} : Radiation in STC (1000 W /m²)
M : The number of photovoltaic modules
K : Temperature coefficient for power modules in ° C
T_C : Cell temperature in °C
T_R : Reference temperature (25°C)

Photovoltaic modul used in this study is SolarexMSX-83 [9]. Because in this study, photovoltaic to be modeled has a rating of 25 kW, then parameters used in this system as follows:

Number of Modules = 302
Maximum power when the STC (PSTC) = 25 kW
Voltage when maximum power = 17.1 V
Flow when maximum power = 4.85 A
Flow short circuit when STC = 5.27 A
Voltage of short circuit when STC = 21.2 V
Temperature coefficient for power (k) = -0.5

E. Wind turbine

Because in this study required wind turbine with a rating of 40 kW, then it will use two wind turbine with 20kW ReDriven type. The power curve of the wind turbine is as follows:
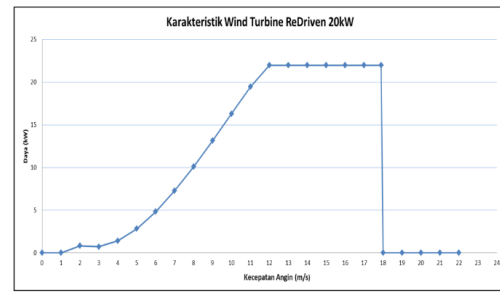

Figure 3. The power curve of ReDriven 20kW models.

From model of the power curve can be obtained as the following equation:
P_{WT} $= 0$ $V_{ac} < V_{ci}$
P_{WT} $= AV_{3ac} + BV_{2ac} + CV_{ac} + d$ $V_{ci} \leq V_{ac} \leq V_r$
$P_{WT, r}$ $= 0$ $V_r \leq V_{ac}$ and $V_{co} < V_{ac}$

Where:
P_{WT} : the power output of the wind turbine in kW
P_{co} : power when the *cut-outs* in kW
V_r : rated speed of the wind in m/s
V_{ac} : wind speed real-time in m/s
V_{ci} : cut-in speed in m/s
V_{co} : cut-out speed in m/s

Based on the curve of wind turbine described above, we can obtain the data related to the performance of the wind turbine, the mathematical equation that could we obtain by curves above are the following parameters:
a = -0.0196
b = 0.5874
c = -2.6814
d = 4.0076
P_{co} = 0
V_{ci} = 2
V_{co} = 18
V_r = 11

F. Fuel Cell.

The operating costs of the fuel cell can be expressed as a function of output power and can be modeled with quadratic polynomial. Operating costs for the fuel cell is as follows:

$$CF (PFC) = aP^2_{FC} P + b_{FC} + c \qquad (6)$$

Where:
CF (PFC): the total cost of operating *the fuel cell* (€ / h)
a, b, and *c:* coefficient generator
PFC: the power output of the *fuel cell* (kW)

In this study used a fuel cell 25 kW which has the function of the cost of fuel taken from reference [10].
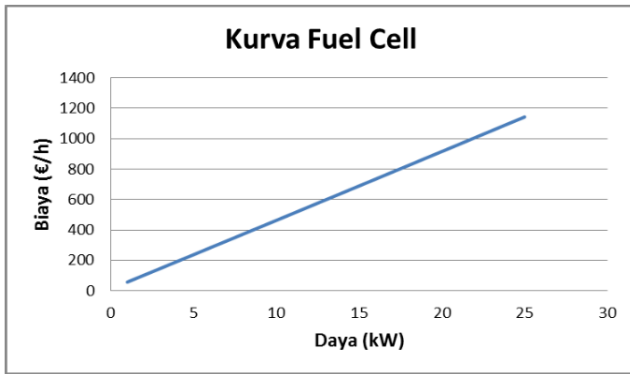
Figure 4. Curve of fuel cell costs.

the above curve is obtained from the following parameters:
a = 0:01
b = 45
c = 12

D. *Micro Turbine*

Operation costs of *micro turbine* can be expressed as a function of output power and can be modeled with a quadratic polynomial. The function of the operating costs for *a micro turbine* is as follows:

$$CF\ (P_{MT}) = aP^2_{MT} + b\ P_{MT} + c$$

Where:
$CF\ (P_{MT})$: total cost of operating the micro turbine (€ / h)
a, b, and *c* : generator coefficient
P_{MT} : the power output of the micro turbine (kW)

In this study used a micro turbine of 75 kW which has the function of the cost of fuel taken from reference [10]. The fuel cost curve is as follows:
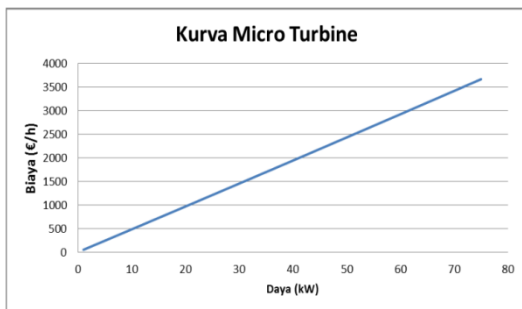

Figure 5. Curve of fuel costs of Micro Turbine

above the curve obtained from the following parameters:
a = 0:01
b = 48
c = 12

E. *Diesel Generator*

Operating costs for the diesel generator is modeled as a quadratic function as follows:

$$CF\ (P_{DG)} = (aP^2_{DG} + b\ P_{DG} + c)$$

Where:
$CF(P_{DG})$: total operating costs of diesel generator (€ / h)
a, b, and c : coefficient generator
P_{DG} : the power output of the diesel generator (kW)

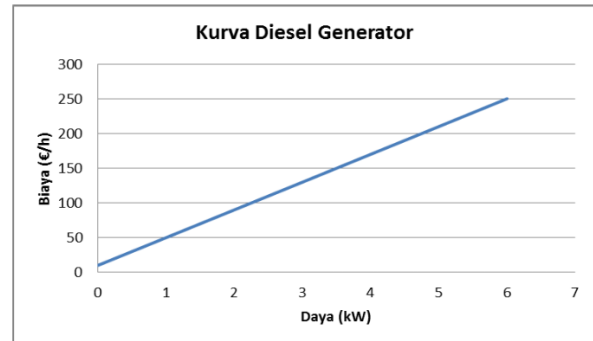In this study used a *diesel generator* 50 kWthat has the function of the cost of fuel taken from reference [10].

Figure 6. Curve of fuel costs of Generator Diesel

above the curve obtained from the following parameters:
a = 0:01
b = 40
c = 10

F. *Battery*
The battery model used in this study were taken from the battery model based on reference [11]:

$CF\ (P_{batt})$ = 0.003831 *Pbatt* (€ / h)
$P_{minbatt}$ = 60 kWh
$P_{maxbatt}$ = 300 kWh
$P_{charge\ min}$ = 0 kW
$P_{charge\ max}$ = 30 kW

Where:
$CF\ (P_{batt})$: total operating cost of battery (€ / h)
P_{batt} : the power output of the battery (kW)
$P_{minbatt}$: capacity minimal power from the battery (kWh)
$P_{maxbatt}$: maximum power capacity of the battery (kWh)
$P_{chargemin}$: minimum operating power from the battery (kW)
$P_{chargemax}$: maximum operating on battery power (kW)

IV. CASE STUDY

Calculation results will be displayed in the form of tables that include the generation of optimal total cost, the direction of power flow battery and battery capacity under various conditions of solar radiation and wind speed. The results of this simulation will show the comparison of application methods on several case studies. There are four case studies that present the possibility occurred variation in system. Micro

grid load conditions during the 24 period of time (1 day) in this study is assumed to be the same for each case study. In this case study will analyze the influence of battery as well as correspond to solar radiation and wind speed to the total cost. In this study the cost of maintenance and purchasing/ procurement component is ignored.

TABLE I. DESCRIPTION OF CASE STUDY

A Case Study of	Solar Radiation and Wind Speed	Battery
1	Constant	Not connected
2	Constant	Connected
3	Varies	Not connected
4	Varies	Connected

Input for case studies 1 and 2 is on the table 2 and then input case studies 3 and 4 there in table 3

TABLE II. DATA AND INPUT CASE STUDY 1 CASE STUDY 2

Time	Total Load (kW)	Wind Speed (m/s)	Irradiance (W/m²)	Temperature(°C)
1	25	10	1000	30
2	30	10	1000	30
3	35	10	1000	30
4	40	10	1000	30
5	53	10	1000	30
6	57	10	1000	30
7	73	10	1000	30
8	84	10	1000	30
9	95	10	1000	30
10	134	10	1000	30
11	141	10	1000	30
12	137	10	1000	30
13	189	10	1000	30
14	175	10	1000	30
15	166	10	1000	30
16	97	10	1000	30
17	82	10	1000	30
18	106	10	1000	30
19	105	10	1000	30
20	117	10	1000	30
21	120	10	1000	30
22	93	10	1000	30
23	20	10	1000	30
24	17	10	1000	30

TABLE III. INPUT DATA CASE STUDY CASE STUDY 3 AND 4

Time	Total Expenses (kW)	Wind Speed (m /s)	Solar Radiation (W / m2)	temperature (Celsius)
1	25	5	0	25
2	30	5	0	25
3	35	5	0	25
4	40	5	0	25
5	53	5	50	25
6	57	5	200	30
7	73	5	200	30
8	84	10	500	30
9	95	10	500	30
10	134	10	1000	30
11	141	10	1000	30
12	137	10	1000	30
13	189	10	1000	30
14	175	10	1000	30
15	166	10	1000	30
16	97	5	500	30
17	82	5	200	30
18	106	5	200	30
19	105	5	50	30
20	117	10	0	30
21	120	10	0	25
22	93	10	0	25
23	20	10	0	25
24	17	10	0	25

V. ANALYSIS STUDY

In this part of the case study conducted dynamic economic dispatch using the energy storage based on quadratic programming method. First case study uses constant weather conditions and is not connected to the battery. Second case study uses constant weather conditions and connected to the battery. While the Third case study uses variable weather conditions and is not connected to the battery, and fourth case study uses varied weather conditions and connected with battery. By using the same load level for each period of time, here is the total cost of generating each case study in Table 4.

TABLE IV. COMPARISON OF TOTAL GENERATION COST

No.	Case Study	Total generation Cost (€)
1	Case Study 1	43563.4442
2	Case Study 2	32699.4988
3	case Study 3	66334.1250
4	Case Study 4	60401.4239

From all case studies that have been simulated, several information are obtained such as the optimum power of each generator, power level of battery for each period of time as well as the total generation cost. Because in each case study used the same load level for each period of time (24 hours), it can be seen that:

a. The total power generated is always equal to the level requested load because the losses are not considered in the system.

b. Renewable generation is for the first priority is photovoltaic compared with wind turbine because of photovoltaic is more stable.

c. The operation of the battery is a top priority compared to the thermal power plants. After the use of battery, the operation of the diesel generator operation has priority because it has cheaper operating costs compared to other thermal power. While micro turbine to get the last priority in the operation because it has the most expensive operating costs.

VI. CONCLUSION

Based on the results of the simulation and analysis of dynamic economic dispatch using quadratic programming which is applied in a system with a variety of power plant generation it can be concluded that quadratic programming can be used to determine the loading of each plant in the system of *micro grid* to obtain the most cost minimal. The use of energy storage device capable of reducing the total cost of the whole. On the condition of solar radiation and wind speed is a constant that is the case study 1 and case study 2 obtained total cost of € 43563.4442 and € 32699.4988. Then, on the condition of solar radiation and wind speed which varies the third case studies and fourth case studies are obtained a total cost of € 66334.1250 and € 60401.4239. Weather conditions significantly give the impact to the total power generation.

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