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Capacity Optimizing method of Distributed Generators in Stand-Alone Microgrid Considering Grid Link-Characteristics

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Abstract – Recently, more power facilities are needed to cope with the increasing electric demand. However, the additional construction of generators, transmission and distribution installations is not easy because of environmental problems and citizen's complaints. Under this circumstance, a microgrid system with distributed renewable resources emerges as an alternative of the traditional power systems. Moreover, the configuration of power system changes with more DC loads and more DC installations. This paper is written to introduce an idea of a genetic algorithm-based solution to determine the optimal capacity of the distributed generators depending on the types of system configuration: AC-link, DC-link and Hybrid-link types. In this paper, photovoltaic, wind turbine, energy storage system and diesel generator are considered as distributed generators and the feasibility of the proposed algorithm is verified by comparing the calculated capacity of each distributed resource with HOMER simulation results for 3 types of system configuration.

Keywords: Capacity optimization, Microgrid, Distributed generators, Genetic algorithm, HOMER.

1. Introduction

In Korea, from 2005 up until 2014, the total consumption of electricity increased by 4.1%, and the maximum demand of electricity increased by 4.4%. In 2014, the total electric consumption was 477,592GWh and the maximum electric demand was 80,154 MW. In order to cope with the continuously increasing electric demand, it is necessary to construct more power supply facilities including generators, transmission and distribution installations. However, it is not easy to build the additional power facilities because of potential conflicts such as environmental problems and citizen's complaints about expansion of the facilities. As its alternative, renewable energy sources (RES) which have little impact on the environment are spotlighted now. RES generates electricity by using natural environments such as solar and wind. They have some advantages of being eco-friendly and very low maintenance costs. On the other hand, they have some disadvantages of high installation cost, irregular and unpredictable power outputs.

According to the official announcement, Korean government is willing to increase the proportion of renewable energy generation capacity from 4.5% to 11.7% and the proportion of renewable energy facilities from 7.5% to 20.1% by 2029. The government enforces the dissemination policy of RES with microgrid to improve the efficiency of using RES [1-3]. The microgrid is a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundary. It divides into grid connection type and stand-alone type. A grid connection type is linked with the main power-supplying network, whereas a stand-alone type is separated from the main network.

And another trend is DC power system. EPRI (Electric Power Research Institute) report says that DC loads will occupy more than 50% of loads in 2020 [4].

As DC loads and RESs increase in AC power system, the following problems occur: (1) the power conversion loss increases in proportion to the rate of DC loads and DC power sources like PV, (2) more power converters interconnecting RESs and loads are needed and it makes the investment cost increase [5].

This condition leads to the active development and technical achievement about DC microgrid including MVDC and LVDC as well as HVDC [6-8].

The microgrid system generally consists of photovoltaic (PV), wind turbine (WT), energy storage system (ESS) and other power suppliers. The required capacity of each distributed generator and ESS is determined by considering the influences between each other in stand-alone microgrid. For example, ESS stores the surplus power when the power generation by RES exceeds the load level, and supplies the stored energy when the output of RES cannot satisfy the load level. Therefore, it is important to construct an optimal power supplying system including ESS and RES by considering the load characteristics of the islands and the economical aspect of distributed generators' capacity.

Many researches on the optimal sizing and scheduling of distributed generators in microgrid have been studied [9-14]. In [15] and [16], pareto-optimal method and fuzzy

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logic have been used for modeling microgrid system, respectively. [17] has determined the capacity of ESS by using Dynamic Programming(DP) for optimal operation schedule and minimum operating cost of the Vanadium Redox Battery in both Grid-connected and stand-alone microgrids, where the optimization was performed at time-based interval of a day. The above three papers focus on the ESS operation in the existing microgrid only and do not estimate the optimal capacity of other distributed generators. To meet the economic feasibility and reliability of microgrid, it is necessary to study the capacity of the distributed generators by a sufficiently long-time simulation. [18] introduced a method to predict solar irradiance and wind speed by using Multi-Objective genetic algorithm (MOGA). The result can help us to determine the location of distributed generators in a DC microgrid. PV output is calculated by the simple product of efficiency, insolation and installation area. Similarly, WT output is obtained by the product of power(P)-wind speed(v) ratio, wind-speed and installation area. In [19], the solar irradiance and wind speed are predicted by using Two-Stage Stochastic Integer Programming and Robust Optimization. [20] introduced how to determine the optimal capacity of diesel generator, photovoltaic, wind turbine and 3 types of energy storage system(ESS) by minimizing the microgrid construction cost. Since each type of ESSs has quite different charge/discharge cycle and cost, it has different optimal capacity depending on the ESS type. The output of PV is determined with global horizontal radiation, constant efficiency (20%) and rated capacity. And the output of WT is calculated by using the wind generator output formula. [21] suggested an optimal operation scheduling method to meet heat and electric demands while minimizing environmental and investment cost using PV, WT, Combined Heat and Power (CHP), fuel cell and microturbine. However, the efficiencies of the generators and power converter have not been considered, and the case study period is only one day, which is not suitable for determining the optimum capacity. The purpose of [22] is to minimize net price cost(NPC) and carbon dioxide emissions during a total life cycle of microgrid. The optimization variable is the capacity of diesel generator. The power delivered to loads is generated primarily by ESS and D/G. The ESS is charged by RES and D/G. However, charging the ESS with D/G is equivalent to using the D/G as it is, so greenhouse gas emissions may not be reduced. And it has lower efficiency, comparing with D/G because of charge/discharge efficiency. [23] presents how to estimate the capacity of distributed generators in AC and DC microgrid system. It analyzed the optimization results depending on the DC load ratio and the inverter/converter efficiency. In [23], the maximum capacity of distributed generators: 16MW (gas generator), 1.5MW (fuel cell) and 2MW (PV and WT) are fixed. Regardless of the DC load ratio, more than 8MW gas generator and 2MW PV are selected and 4.44MWh ESS with 1MW PCS is selected only at 100% DC load. As a result, the optimal process in [23] does not consider the reduction of greenhouse gas emissions. In addition, the proportion of gas generators in the microgrid is larger than that of renewable energy resources, and this is contrary to the expansion policy of renewable energy resources. Taken together all above papers, we can reach a conclusion as follows: (1) calculate the energy flow about 1 year for appropriate results; (2) consider the efficiency of AC/DC and DC/AC power converter and ESS; (3) maximize the use of renewable energy resources by reducing environmental pollution; (4) ESS is charged only renewable energy resources; (5) optimization is performed three different linkage types for changing power system and load characteristics.

This paper considers a stand-alone type microgrid of an island where the power is supplied by PV, WT, ESS and diesel generator. At first, simulation models and their components are explained in detail for three different system linkage types: DC-link, AC-link and AC/DC hybrid link. At next, genetic algorithm-based optimization method is introduced to determine the optimal capacity of distributed generators for the three different system configurations. Each simulation is separated into two cases: one is with diesel generators and the other is without them. The reason for dividing two cases is that the capacity of RES and ESS is affected depending on the operation time of D/G. Finally, the calculated capacities are compared with the results simulated by HOMER, the most reliable and world-widely used program [24-26].

2. Preparation System Modeling for Simulation

The selected site for this research is Gasa island in Korea. It is separated from the main grid and its electric power is mainly supplied by diesel generator(D/G). Since the island is not a famous tourist site but a typical fishing village, its electric load keeps very low during daytime and maximum at early evening, as shown in Fig. 1. It shows the hourly averaged graph of 1-year load data of the island.

We assume that PV, WT, D/G and ESS supply the electric power in a stand-alone microgrid. Capacities of the distributed generators are set to a specific value according to the manufacturer in the real world. The basic capacity units of the distributed generators in the simulation are 50kW for diesel generator, 1kW for PV, 100kW for WT and 1kWh for ESS. This system simulates the operation of a system by performing energy flow calculations at each time step during the project period. In Case 1, we include a diesel generator(D/G), which means that the island aims to be an energy independence island like a stand-alone microgrid. D/G is only used when the power generated by RESs is smaller than the load. And it is not stored energy in the ESS. In Case 2, we exclude a diesel generator, which means that it aims to be a carbon-free island.

Table 1 shows the information on total capital,

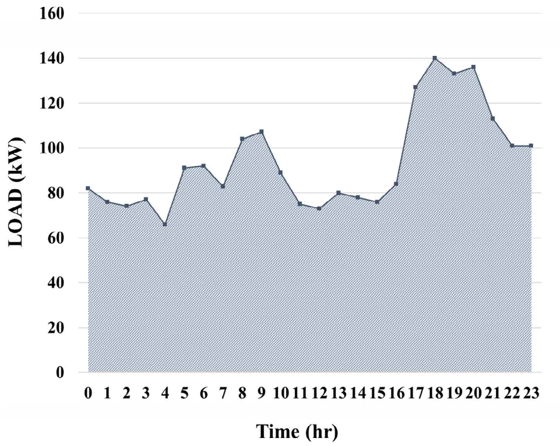

Fig. 1. Average hourly electrical load of 1-year

Table 1. Cost information and efficiency of distributed generators

Gen	Capital (＄/kW)	Replacement (＄/kW)	O&M (＄/kW)	Efficiency (%)
PV	3,065	2,452	22/year	86
WT	5,297	3,919	35/year	29
ESS	1,159	270	6.5/year	75
D/G	1,700	1700	0.09/hour	30

replacement cost, O&M (Operation and Maintenance) cost and efficiency. All the cost information is used as average cost per kW of internal and external markets [27-31]. The capacity of distributed generators is calculated to minimize the total net present cost(NPC) which includes all costs and revenues within the entire project duration. How to calculate NPC will be described in detail at Section 3.

Efficiencies of PV, WT and D/G are derating factor, power coefficient and electric generating efficiency, respectively. Derating factor of PV is a scaling factor accounting for the PV's reduced output in the real-operating conditions, compared to the rated conditions. Wiring losses, shading and aging, etc. are included in the derating factors. Power coefficient of WT is a factor used for estimating the output of WT with wind speed. The efficiencies of D/G are divided into generating efficiency, heat-recovery efficiency, total efficiency and utilization efficiency. In this study, because D/G is used to supply the electric power only, the efficiency of D/G means electric generating efficiency, which is calculated as a ratio of generated power to fuel consumption. And the efficiency of ESS means a product of AC/DC and DC/AC conversion efficiencies.

2.1 Environmental factors

Various environmental factors such as degree of cleanliness, solar radiation and temperature should be considered when calculating the outputs of PV and WT. In this paper, we obtained the temperature data from the homepage of Korea Meteorological Agency, the cleanliness and radiation data from NASA Surface Meteorology and Solar Energy.

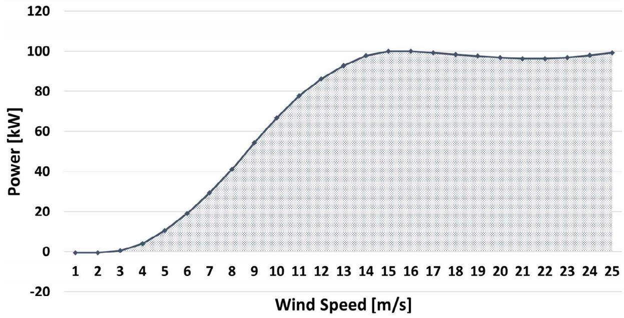

Fig. 2. Wind speed vs. Power output of WT

For PV, Eq. (1) is used to calculate its output. G_{ref} and f_{PV} are reference radiation (1000 kW/m^2) and PV derating factor, respectively. For wind power generation, generator type, wind speed and power coefficient are important factors for the output estimation. Wind speed data used in the simulation are re-calculated from 1-minute actual wind power data(kW) acquired at the different island sites for 1 year. Normalized data of wind power generation in the island is obtained by inputting the above-mentioned wind speed into the power curve of a wind turbine used in the actual simulation island. The power curve is shown in Fig. 2 [32].

$$PV_i = X_{PV} f_{PV} \frac{G_i}{G_{ref}} \tag{1}$$

2.2 AC-link modeling

The AC-link system architecture consists of AC bus only. Since PV and ESS generate DC power, they need a DC/AC inverter for converting DC to AC power. Eqs. (2) - (9) describe a power flow in the AC-link system.

$$AC_i = WT_i - LOAD_i \tag{2}$$

$$\begin{cases} DC_i = X_{inv}, if\ PV_i \times \eta_{inv} \geq X_{inv} \\ DC_i = PV_i \times \eta_{inv}, if\ PV_i \times \eta_{inv} < X_{inv} \end{cases} \tag{3}$$

$$ESS_i = AC_i + DC_i \tag{4}$$

$$\begin{cases} ESS_i' = ESS_i \times \eta_{ESS}, if\ ESS_i \geq 0 \\ ESS_i' = ESS_i \div \eta_{ESS}, if\ ESS_i < 0 \end{cases} \tag{5}$$

AC_i is the required power in the AC bus at time step i. The value of AC_i is calculated by subtracting the load level from the wind power generation at i. In the Eq. (2), the power generated by the diesel generator is not included because the renewable energy resources have a higher priority in the stand-alone microgrid. X_{inv} means the capacity of PV inverter. DC_i, which means the AC-link

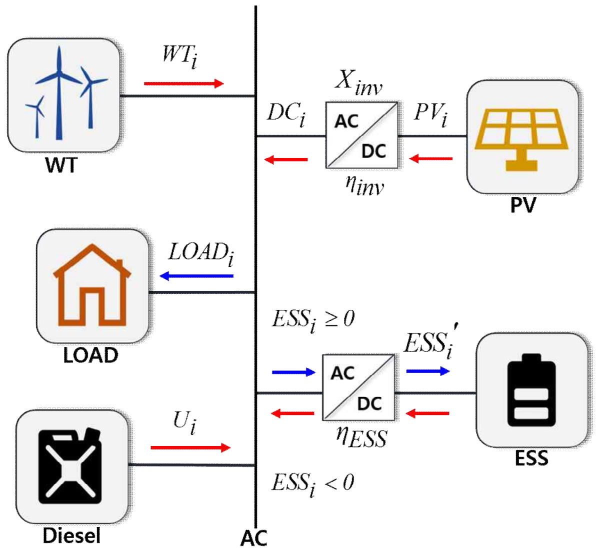

Fig. 3. Simple diagram of AC-link system architecture

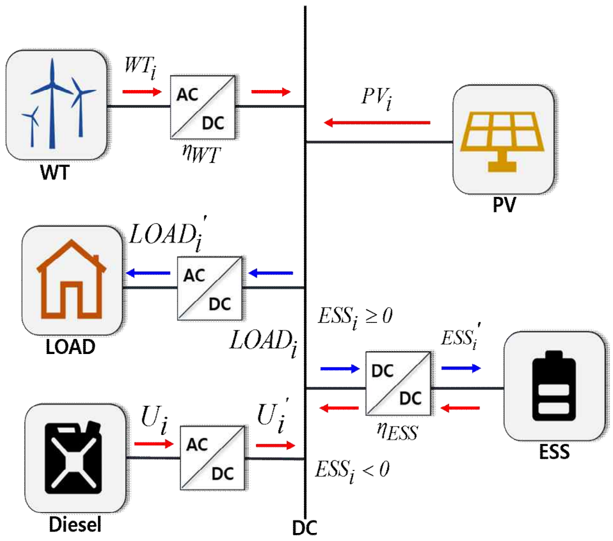

Fig. 4. Simple Diagram of DC-link system architecture

output of PV at i, is determined as X_{inv} when the output of PV inverter with inverter efficiency η_{inv} is greater than or equal to X_{inv}. This is because the output of PV system cannot exceed the inverter capacity. In other words, if the power generated by PV exceeds the inverter capacity, the inverter capacity becomes the available PV power as shown in (3). ESS_i is the required charge/discharge amount of ESS at the time step i, whose value represents the sum of AC_i and DC_i at the system side. ESS_i' means the power at the real ESS side, considering the PCS (Power Conversion System) efficiency of η_{ESS}. If ESS_i is positive, it represents the charging state. Otherwise, it represents the discharging state.

$$\begin{cases} SOC_0 = 1 \\ SOC_i = EC_i \div X_{ESS} \end{cases} \quad (6)$$

$$\begin{cases} EC_i = X_{ESS}, \text{if } ESS_i' + SOC_{i-1} \times X_{ESS} \geq X_{ESS} \\ EC_i = 0, \text{if } ESS_i' + SOC_{i-1} \times X_{ESS} < 0 \\ EC_i = ESS_i' + SOC_{i-1} \times X_{ESS}, \text{otherwise} \end{cases} \quad (7)$$

$$\begin{cases} R_i = X_{ESS} - EC_{i-1}, \text{if } EC_{i-1} + ESS_i' \geq X_{ESS} \\ R_i = -EC_{i-1}, \text{if } EC_{i-1} + ESS_i' < 0 \\ R_i = ESS_i, \text{otherwise} \end{cases} \quad (8)$$

$$\cdot \begin{cases} U_i = abs(ESS_i) - abs(R_i) \times \eta_{ESS}, \text{outage} \\ U_i = 0, \text{otherwise} \end{cases} . \quad (9)$$

SOC_i represents the state of charge of ESS at time step i. Its initial value, SOC_0, is assumed 100%, that is, fully charged as shown in (6). EC_i is the energy stored in the actual ESS and R_i is the real charge or discharge amount of the ESS at time step i. X_{ESS} represents the ESS capacity of kWh unit that we want to determine from the following optimization. If the chargeable energy exceeds the maximum storage capacity of the ESS, it maintains the maximum capacity. And if the required discharge amount exceeds the energy stored in the ESS, it keeps the SOC of '0' after discharging the energy remaining in the ESS. U_i is the amount of power generated by diesel generators in the simulation Case 1.

2.3 DC-link modeling

The DC-link system architecture consists of DC bus only. Loads, wind turbines and diesel generators consume or generate their power in the form of AC. Therefore, in this DC link model, we need AC/DC converters at the DC-link side. To use preferentially the power of renewable energy resources, the converters used at loads and wind turbines allow the conversion of all required amount, regardless of their capacity. Eqs. (10) - (17) represent the power flow in DC-link model.

$$LOAD' = LOAD \times \eta_{inv} \quad (10)$$

$$DC_i = WT_i \times \eta_{WT} - LOAD_i \quad (11)$$

$$ESS_i = DC_i + PV_i \quad (12)$$

$$\begin{cases} ESS_i' = ESS_i \times \eta_{ESS}, \text{if } ESS_i \geq 0 \\ ESS_i' = ESS_i \div \eta_{ESS}, \text{if } ESS_i < 0 \end{cases} \quad (13)$$

LOAD' and $LOAD_i$ mean the required powers at the load side and the DC-bus side respectively. *LOAD'* is calculated with DC/AC inverter efficiency η_{inv} and $LOAD_i$ as shown in (10). DC_i is the required power in the DC bus at the time step i. The value of DC_i is calculated by subtracting the load demand level from the power generated by wind turbines considering the converter efficiency of WT (η_{WT}) at time step i. PV_i is the power generated by PV. ESS_i is the required power for charging or discharging ESS at time step i, which is calculated by the summation of PV_i and DC_i. Positive value of ESS_i means the charging state and negative ESS_i represents the discharging state. $ESS_i{'}$ means the power at the real ESS side, considering the PCS efficiency of η_{ESS}.

$$\begin{cases} SOC_0 = 1 \\ SOC_i = EC_i \div X_{ESS} \end{cases} \tag{14}$$

$$\begin{cases} EC_i = X_{ESS},\ if\ ESS_i^{'} + SOC_{i-1} \times X_{ESS} \geq X_{ESS} \\ EC_i = 0,\ if\ ESS_i^{'} + SOC_{i-1} \times X_{ESS} < 0 \\ EC_i = ESS_i^{'} + SOC_{i-1} \times X_{ESS},\ otherwise \end{cases} \tag{15}$$

$$\begin{cases} R_i = X_{ESS} - EC_{i-1},\ if\ EC_{i-1} + ESS_i^{'} \geq X_{ESS} \\ R_i = -EC_{i-1},\ if\ EC_{i-1} + ESS_i^{'} < 0 \\ R_i = ESS_i,\ otherwise \end{cases} \tag{16}$$

$$\begin{cases} U_i = X_{conv} \div \eta_{conv},\ if\ U_i^{'} \geq X_{conv} \\ U_i = abs(ESS_i^{'} - R_i \times \eta_{ESS}),\ if\ U_i^{'} < X_{conv} \\ U_i = 0,\ otherwise \end{cases} \tag{17}$$

SOC_i represents the state of charge of the ESS at the time step i. Its initial value, SOC_0, is set 100% as shown in (14). EC_i is the energy stored in the actual ESS and R_i is the real charge or discharge amount of the ESS at time step i. X_{ESS} represents the ESS capacity of kWh unit that we want to determine from the following optimization.

U_i is the amount of power generated by diesel generators in the simulation Case 1, which can be affected by the converter capacity. $U_i{'}$ is the amount of generated power, regardless of the converter capacity.

2.4 Hybrid-link Modeling

Hybrid-link system architecture consists of both DC and AC buses. Each distributed generator is connected to the same type of bus as its power. That is, PV, ESS are connected into DC bus and WT, load, D/G are connected into AC bus. Therefore, only one system converter between AC and DC bus is added instead of individual converters or inverters for each distributed generator. The system converter operates as AC/DC converter and DC/AC inverter. The capacity of converter is determined by the generated power of WT to store the energy in ESS and inverter is determined by the load. Capacity of the system converter is determined by the larger of the two capacity values. Eqs. (18) - (25) describe the power flow in the Hybrid-link.

$$AC_i = WT_i - LOAD_i \tag{18}$$

$$\begin{cases} AC_i^{eff} = X_{conv},\ if\ AC_i \times \eta_{conv} \geq X_{conv} \\ AC_i^{eff} = AC_i \times \eta_{conv},\ if\ AC_i \times \eta_{conv} < X_{conv} \end{cases} \quad if\ AC_i \geq 0 \tag{19}$$

$$\begin{cases} AC_i^{eff} = -X_{conv},\ if \left| AC_i \div \eta_{conv} \right| \geq X_{conv} \\ AC_i^{eff} = AC_i \div \eta_{conv},\ if \left| AC_i \div \eta_{conv} \right| < X_{conv} \end{cases} \quad if\ AC_i < 0 \tag{20}$$

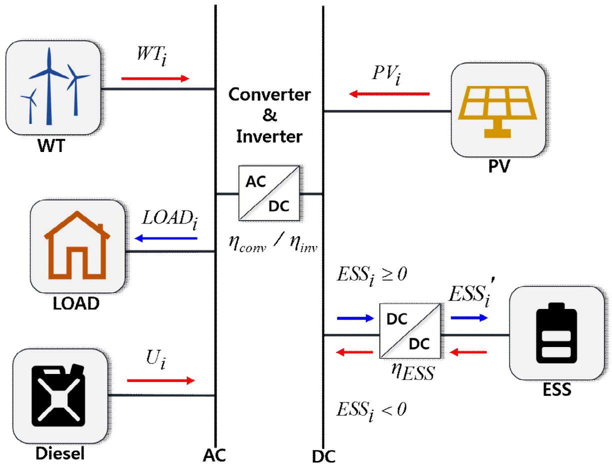

Fig. 5. Simple Diagram of Hybrid-link system architecture

$$ESS_i = AC_i^{eff} + PV_i \tag{21}$$

$$\begin{cases} ESS_i^{'} = ESS_i \times \eta_{ESS},\ if\ DC_i \geq 0 \\ ESS_i^{'} = ESS_i \div \eta_{ESS},\ if\ DC_i < 0 \end{cases} \tag{22}$$

AC_i is the required power in the AC bus side. The value of AC_i is calculated by subtracting the load level from the wind power generation at i. X_{conv} means the capacity of system converter. If AC_i is positive, the power flows from AC bus into DC bus and ESS is charged. AC_i^{eff} which means the stored power at DC side, is determined as X_{conv} when AC_i output of AC bus with converter efficiency η_{conv} is greater than or equal to X_{conv} as shown in (19). If AC_i is negative, the power flows from DC bus into AC bus and ESS is discharged. AC_i^{eff}, which means the discharged power at DC side, is determined as X_{conv} as shown in (20). This is because both outputs of AC and DC bus cannot exceed the system converter capacity. ESS_i is the required charge/discharge amount of ESS at the time step i, whose value represents the sum of AC_i^{eff} and PV_i. $ESS_i{'}$ means the power at the real ESS side, considering the PCS efficiency of η_{ESS}. If ESS_i is positive, it represents the charging state. Otherwise, it represents the discharging state.

$$\begin{cases} SOC_0 = 1 \\ SOC_i = EC_i \div X_{ESS} \end{cases} \tag{23}$$

$$\begin{cases} EC_i = X_{ESS},\ if\ ESS_i^{'} + SOC_{i-1} \times X_{ESS} \geq X_{ESS} \\ EC_i = 0,\ if\ ESS_i^{'} + SOC_{i-1} \times X_{ESS} < 0 \\ EC_i = ESS_i^{'} + SOC_{i-1} \times X_{ESS},\ otherwise \end{cases} \tag{24}$$

$$\begin{cases} R_i = X_{ESS} - EC_{i-1},\ if\ EC_{i-1} + ESS_i^{'} \geq X_{ESS} \\ R_i = -EC_{i-1},\ if\ EC_{i-1} + ESS_i^{'} < 0 \\ R_i = ESS_i,\ otherwise \end{cases} \tag{25}$$

$$\begin{cases} U_i = (\left|R_i\right| \times \eta_{ESS} + PV_i) \times \eta_{inv} + AC_i,\ outage \\ U_i = 0,\ otherwise \end{cases} \tag{26}$$

SOC_i represents the state of charge of the ESS at the time step i. Its initial value SOC_0 is assumed 100% as shown in (23). EC_i is the energy stored in the actual ESS and R_i is the real charge or discharge amount of the ESS at time step i. X_{ESS} represents the ESS capacity of kWh unit that we want to determine from the following optimization. U_i is the amount of power generated by diesel generators in the simulation Case 1.

3. Optimization

3.1 Genetic algorithm

The genetic algorithm is a parallel and global optimization technique developed by John Holland. It is a computational model based on the evolution process of natural selection. It represents possible solutions in a form of data structure and finds suitable data structure by transforming the value called as 'gene' in data structure. Genetic algorithm has a population and then selects n solutions from the initial population. n solutions perform selection, crossover and mutation operations to generate k solutions. k solutions are respectively performed fitness evaluation and replaced with the solutions of the initial population. If the value of the population exceeds a proper value, the operations are terminated, and the result is returned.

Selection is an operation to select parent solutions for the next generation. The parent solutions are used to operate crossover and mutation. Generally, the best solutions are chosen for the parent solution by using Stochastic uniform, Roulette Wheel, Tournament, Rank-based methods and so on. In this paper, we used Stochastic uniform method. It has a line of 0~F length and each solution occupies the length of its fitness value in the line. In this case, the solutions are sorted as the greatest fitness in line, and the F/k-length pointer selects k solutions.

Crossover operation generates the solutions of next generation by using parent solutions. One-point and Multi-point crossovers generate the next solution by using the radial line. Otherwise, the uniform crossover generates the next solution by using a random binary vector. Since diversity of breeding is higher than other method, uniform method is selected in this paper. In Fig. 6, a solution is generated by taking a value from p_1 if binary vector is 1, and from p_2 if 0.

Mutation is a forced change in the value of any part of solution. This technique is used to prevent falling into a local optimal solution, and to ensure the diversity of the population.

3.2 Economic analysis

NPC (Net Present Cost) is a concept used for the economic analysis of system during the whole project period. All costs and revenues occurring during the project period are included in NPC. It can calculate the cash flow by applying a discount rate.

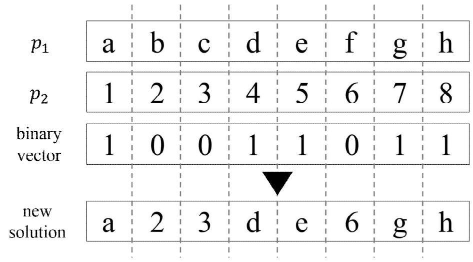

Fig. 6. Example of Uniform crossover

NPC should include the initial investment cost, the replacement cost, and the maintenance cost of the resources, because each cost characteristic varies depending on the type of distributed generator. The initial investment cost means the installation cost of the distributed generators. The replacement cost is calculated by considering the lifetime of the distributed generators during the project period. The maintenance and operation costs are incurred annually.

To calculate NPC accurately, information such as discount rate(R_{dis}) and inflation rate(R_{inf}) is needed. In May 2016, the Bank of Korea notified the discount rate and the inflation rate. The discount and inflation rates are 1.5% and 1.3%, respectively. Real discount rate(α) is calculated with R_{dis} and R_{inf} by (27). The discount factor(D) in the project duration (total P years) changes every year, which can be obtained by (28).

The revenue is included in the NPC calculation as the salvage value for the remaining life. That is, if the lifetime of distributed generators remains within the duration of project, the cost for the remaining lifetime is returned as revenue, which is calculated by a linear depreciation.

$$\alpha = \frac{R_{dis} - R_{inf}}{1 + R_{inf}} \tag{27}$$

$$D(\alpha, N) = \frac{1}{(1+\alpha)^N}, \; N = 1, 2, \cdots, P \tag{28}$$

3.3 Cost equation

The cost equations to calculate the cost of the distributed generators in a microgrid are shown in (29) - (34). In this paper, we use a genetic algorithm (GA) to minimize the total cost and to find the wide-range optimal solutions with a high probability. X represents the capacity of each distributed generator and its subscript indicates the type of facilities. $C_{capital}$, $C_{replacement}$, $C_{O\&M}$ represent initial investment cost, replacement cost and operation & maintenance(O&M) cost, respectively. E means the year that the alternative cost of each distributed generator occurs.

T_{DG} (hours/1year) means the time-duration for which diesel generators operate. The reason for multiplying the maintenance cost in (32) is that the maintenance cost is related to the diesel operation time due to the characteristic of the diesel. $C_{DG,operating}$ is the cost associated with fuel costs as a diesel operating cost. And P_{DG} means amount of annual power generated by diesel generators.

$$C_{PV} = X_{PV} \times [C_{PV,capital} + \sum_{j=1}^{P} D(\alpha, j) \times C_{PV,O\&M} + D(\alpha, E_{PV}) \times C_{PV,replacement}] \quad (29)$$

$$C_{WT} = X_{WT} \times [C_{WT,capital} + \sum_{j=1}^{P} D(\alpha, j) \times C_{WT,O\&M} + D(\alpha, E_{WT}) \times C_{WT,replacement}] \quad (30)$$

$$C_{ESS} = X_{ESS} \times [C_{ESS,capital} + \sum_{j=1}^{P} D(\alpha, j) \times C_{ESS,O\&M} + D(\alpha, E_{ESS}) \times C_{ESS,replacement}] \quad (31)$$

$$C_{DG} = X_{DG} \times [C_{DG,capital} + \sum_{j=1}^{P} D(\alpha, j) \times T_{DG} \times C_{DG,O\&M} + D(\alpha, E_{Inv}) \times C_{DG,replacement}] + C_{DG,operating} \times P_{DG} \quad (32)$$

$$C_{Conv} = X_{Conv} \times [C_{Conv,capital} + \sum_{j=1}^{P} D(\alpha, j) \times C_{Conv,O\&M} + D(\alpha, E_{Conv}) \times C_{Conv,replacement}] \quad (33)$$

$$C_{Inv} = X_{Inv} \times [C_{Inv,capital} + \sum_{j=1}^{P} D(\alpha, j) \times C_{Inv,O\&M} + D(\alpha, E_{Inv}) \times C_{Inv,replacement}] \quad (34)$$

3.4 Optimization formula

Table 2 shows the optimization formula for AC, DC and hybrid system configurations. The constraints vary depending on whether diesel generators are included or not.

T_{outage} is a total outage time. In the Case 1, the outage time is set as '0' for the optimization process, which means that diesel generators operate when the outputs of PV, WT and ESS are insufficient for the load level. S_{day} represents the number of sunless days, which is set as 1-day in comparison with the HOMER result in the Case 2. SOC represents the charging state of ESS. Minimum and maximum SOC are set as 0% and 100%, respectively. The optimization of system model is conducted by MATLAB and the results are compared with HOMER results.

Table 2. Optimization modeling formula

Decision variables	X_{PV} , X_{WT} , X_{ESS} , X_{Inv} , X_{Conv}
AC modeling Objective function	Min ($C_{PV} + C_{WT} + C_{ESS} + C_{Inv} + C_{DG}$)
DC modeling Objective function	Min ($C_{PV} + C_{WT} + C_{ESS} + C_{Conv} + C_{DG}$)
Hybrid modeling Objective function	Min ($C_{PV} + C_{WT} + C_{ESS} + C_{Conv} + C_{DG}$)
Case 1 Constraints	$SOC_{\min} \le SOC_i \le SOC_{\max}$ $T_{outrage} = 0$
Case 2 Constraints	$SOC_{\min} \le SOC_i \le SOC_{\max}$ $S_{day} = 1$

4. Simulation Results

From the optimization by MATLAB engine, we can obtain the optimal solutions such as the installation capacity (kW unit) of PV, WT and diesel generator, the storage capacity (kWh) of ESS and the total cost of NPC ($), which are the cost-minimized system capacities sufficient for the hourly load shown in Fig. 1. Then the results are compared with HOMER to verify the reliability and accuracy of the optimization method proposed in this paper.

In the simulation by HOMER, all values including all environmental conditions, efficiency, and cost are same as used in the optimization modeling.

Since a system cannot be configured with only one bus in the HOMER simulation, the system needs to be simplified and equalized so that it can be compared with the optimization modeling. Tables 3-5 show the optimally determined capacity of the distributed generators for each system. In the Case 1, the diesel generators are considered as one of the resources. In the Case 2, they do not operate. For the case of Only D/G, only diesel generators operate without distributed generators. In Table 3 and 5, diesel generators are connected to AC-link, while in Table 4 they are connected to DC-link. Therefore, NPCs for Only D/G case of Table 3 and 5 are same. And, D/G capacity and NPC for Only D/G of Table 4 is larger than the others of Table 3 and 5 due to DC/AC power conversion loss.

4.1 AC-link simulation result

For the AC-link case, we use the system configuration shown in Fig. 3, which can be formulated by the (2)-(9). Then the optimal solutions are obtained by minimizing the total NPC which is calculated from the Eqs. (29)-(34) under the constraints of Table 2. AC-link simulation results are shown in Table 3.

The simulation results of Case 1 are PV of 292kW, WT

Table 3. AC Simulation result

		PV (kW)	Inv (kW)	WT (kW)	ESS (kWh)	Diesel Gen (kW)	NPC ($)
Only D/G		-	-	-	-	200	10,994,280
Case 1	Our simulation	292	150	300	578	150	5,863,592
	HOMER	265	150	300	690	150	6,472,208
Case 2	Our simulation	1,462	350	200	2,373	-	10,989,407
	HOMER	1,433	350	200	2,431	-	11,019,020

of 300kW, ESS of 578kWh. Generation rate and capacity factor are respectively PV 27% and 14%, WT 60% and 25.18%. Generation rate means the ratio of the generation power of individual resource with respect to the total power generation. And the capacity factor means the utilization factor of energy resources and is calculated by (35). As a result, the installation capacity of WT is similar to that of PV, but WT generates much more power than PV.

$$Capacity\ Factor = \frac{\dfrac{generated\ power\ of\ resource\,[kWh/yr]}{operating\ time\,[h/yr]}}{capacity\ of\ resource\,[kW]} \tag{35}$$

The simulation results of Case 2 are PV of 1,433kW, WT of 200kW, ESS of 2,431kWh. When comparing with the previous case, in this case, PV increases 5 times, ESS increases 4.1 times and WT decreases slightly. When we ignore the diesel generators, the optimal capacities of PV, WT and ESS increase naturally, because all the energy generated by PV and WT should be stored in ESS in preparation for sunless days and the ESS must supply the power in sunless days instead of diesel generators.

According to Table 3, the inverter capacity is very smaller than the PV capacity. Because PV cannot generate 100% of its output due to derating factor and environmental conditions. The derating factor is set to 86%. The environmental factor is the amount of solar radiation. When the solar radiation is not good, the output is very small compared to the rated PV capacity. If the rated capacity of PV is less than the determined capacity, the capacity of ESS or WT is increased to meet load at bad isolation time. However, the investment cost per kW of WT and ESS is larger than the PV. Therefore, the constant output of PV is abandoned at high insolation time, the capacity is determined to be large. The capacity of inverter should be determined by the amount of required power at high insolation time, because the price per kW of PV's inverter is calculated for minimum NPC.

4.2 DC-link simulation result

DC-link simulation results are shown in Table 4.

Table 4. DC Simulation result

		PV (kW)	Conv (kW)	WT (kW)	ESS (kWh)	Diesel Gen (kW)	NPC ($)
Only D/G		-	-	-	-	200	11,714,720
Case 1	Our simulation	461	134	200	863	150	6,457,751
	HOMER	370	137	200	1,071	150	7,011,732
Case 2	Our simulation	1,467	-	300	2,499	-	11,804,880
	HOMER	1,463	-	300	2,503	-	11,800,520

The simulation results of Case 1 with D/G are PV of 461kW, WT of 200kW, ESS of 863kWh. Generation rate is PV 50%, WT 36%. The simulation results of Case 2 without D/G are PV of 1,467kW, WT of 300kW, ESS of 2,499kWh. Compared with the simulation of Case 1, PV increases 3.2 times, ESS increases 2.9 times and WT increases 1.5 times in Case 2.

To use preferentially the power of renewable energy, the converters used in loads and wind turbines must be able to convert the amount of all required power conversions. In the DC modeling, converters have the only purpose of transferring the output of D/G to the load. Therefore, the converter capacity was not estimated in Case 2. When considering that the average and maximum load levels are 90.19kW and 167kW respectively, the estimated capacity of the converter is appropriate. As shown in Table 3 and 4, the results of Case 2 in both AC and DC models are very similar to each other except WT capacity. Since WT generates AC power, the DC connection of WT has more losses than AC connection. Therefore, the WT capacity in DC modeling is determined much bigger than AC modeling.

4.3 Hybrid-link simulation result

Hybrid-link simulation results are shown in Table 5.

Table 5. Hybrid Simulation result

		PV (kW)	Conv (kW)	WT (kW)	ESS (kWh)	Diesel Gen (kW)	NPC ($)
Only D/G		-	-	-	-	200	10,994,280
Case 1	Our simulation	293	133	300	586	150	5,866,388
	HOMER	223	101	300	495	150	6,497,616
Case 2	Our simulation	1,296	148	300	2,359	-	11,095,576
	HOMER	1,300	172	300	2,400	-	11,942,190

The simulation results of Case 1 with D/G are PV of 293kW, WT of 300kW, ESS of 586kWh. Generation rate is PV 32%, WT 51%. The simulation results of Case 2 without D/G are PV of 1,296kW, WT of 300kW, ESS of 2,359kWh. Compared with those of Case 1, PV increases 4.42 times, ESS increases 4 times in Case 2.

In the hybrid model, the capacity of system converter is mainly affected by WT when converting AC to DC, and by PV and ESS when converting DC to AC. The capacity of converter is estimated smaller than the capacity of WT. This is because the amount of power generated by WT is consumed first by the load and the remaining amount is transferred to the ESS. In addition, it is more cost-effective to discard the power over the converter capacity than to increase the capacity of converter.

When comparing the results of AC and DC link modeling, the capacities of all distributed generators are slightly different from each other. In AC system, the loss of

PV is relatively large. And in DC system, the loss of WT is relatively large. However, in hybrid system, the losses of PV and WT is relatively small, so the estimated capacity in hybrid modeling is relatively smaller than other models.

4.4 HOMER simulation

From Tables 3-5, the similarities between HOMER and our optimization modeling can be observed in all results. In general, NPC of the optimization modeling is less than the HOMER. The main reason for this difference is that ESS operates differently in HOMER program. HOMER calculates maximum chargeable and dischargeable values every hour, considering the physical parameters of ESS, which can also affect total operation time of diesel generators. As a result, the operating time of D/G in the optimization modeling becomes longer than HOMER and other distributed generators have less capacity. From the simulation results by the system configurations, the cost for AC link is the lowest, followed by Hybrid and DC. The reason is that most of the electric loads are connected to AC system. And this result may be different if the types of power that make up the load are different.

5. Conclusion

This paper describes a simple and accurate method to determine the optimal capacities of photovoltaic (PV), wind turbine (WT), and ESS as distributed generators installed in stand-alone microgrid. It is proposed by considering grid link characteristics: AC-link, DC-link and Hybrid-link. NPC, fixed discount and inflation rates are used for the economic analysis. Finally, the simulation results are compared with HOMER simulation, one of the most famous worldwide optimization program, to demonstrate validity and reliability of the proposed optimization methods.

Distributed generators except diesel generator are easily affected by geographical and weather conditions. When estimating the capacity of each distributed generator, ESS which stores the energy produced by distributed generators excluding D/G should be decidedly included in the simulation result. In case that renewable energy resources cannot generate the electric power steadily, ESS must supply the electricity instead of them. That is, diesel generators in Case 1 can be replaced by ESS in Case 2. In general, ESS can operate for longer than 8 hours at night without the power of renewable resources.

In Case 1, the D/G capacity of all grid-link configuration is estimated to be the same, but the capacities of other distributed generators are severally different. The reason is that the operation time is different in the same D/G capacity. Therefore, the performance of Case 2 which is not include D/G should be necessary. In Table 3, inverter capacity is smaller than PV capacity. The reason is that PV does not always generate its rated power. In other words, discarding excess power above the inverter capacity at high insolation is more economical than increasing the capacity of ESS or WT. And increasing PV's capacity is not economical than increasing ESS or WT capacity. In Case 2, the capacity of distributed generators excluding D/G has increased to replace the D/G. Distributed generators have their own type of power generation, AC or DC. And the generator capacities are calculated large when their power generation types are same to the bus type. This is because the efficiency is good for the same type.

Additionally, in this paper, a genetic algorithm-based optimization method was introduced to determine the optimal capacity of distributed generators depending on the system link configuration. Capacity optimization is performed using the actual load data of island. This is verified by HOMER simulation under the same conditions. In 2020, renewable energy is expected to reach the grid-parity, so the results of HOMER and our simulations can be changed depending on the entering cost. The algorithm considers only AC load in this paper. It will be improved considering DC load ratio and uncertainty of wind, insolation and load in the future. Also, we will propose algorithms by adding thermal load and heat generators for more accurate economic analysis of energy mix.

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