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Submission date: 23-Apr-2023 11:28PM (UTC+0700)
Submission ID: 2072794192
File name: C.2.a.2-14_artikel_LOMI.pdf (230.75K)
Word count: 3815
Character count: 23091

Optimization Design Suite for Expandable Micro-Grid Clusters

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***Abstract*— In this study, we introduce an optimization design suite, referred to as the "grid of grids optimal designer" (GGOD), as an addition to the expandable micro-grid clusters (EMGCs) for the evolving electricity generation and infrastructure sectors. EMGCs are an autonomous group of micro-grids in which clusters can generate and consume power. The GGOD is a type of simulation software suitable for long-term use at an electrical facility, where operation planners can plan the expansion, construction, and EMGC operation functions. One of the primary uses of the GGOD is for geospatial data, which require the execution of real world optimization planning. Here, we describe two key applications of the GGOD, including geospatial integrated resource planning for wind farm allocation and transmission configurations, as well as congestion–mitigation planning based on the nodal price approach. Moreover, a concept for the interactive use of optimization functions is also explained.**

***Keywords*— microgrid; expandable micro-grid cluster; grid of grids optimal designer; optimization; geospatial data**

I. Introduction

Electric power systems constitute the fundamental infrastructure of our modern society. However, constructing electrical infrastructure requires significant investment. Thus, micro-grids [1] are increasingly seen as the most promising energy self-reliance systems because they allow for the local production of electricity to satisfy local consumption in a specific area. We refer to this type of micro-grid group as an expandable micro-grid cluster (EMGC).

In this study, an optimization design suite, referred to as the grid of grids optimal designer (GGOD), is introduced for EMGCs. One primary characteristic of GGOD is to manage and analyze geospatial data. By using geospatial data, planning reflecting real topographical conditions can be executed. Geospatial data for renewable energy are called zoning areas [2]. The zoning data are created by overlaying and analyzing map layers, termed the cost surface,. The International Renewable Energy Agency reported on the introduction of geospatial data for strategic long-term planning [3]. In ref [4], a cost surface was constructed for geospatial data to introduced transmission expansion planning. In this paper, a method to extract geospatial data for wind farm (WF) feasible areas is described.

Furthermore, we present some examples regarding the use of the GGOD functions to optimize the construction and operation of EMGCs, including geospatially integrated resource planning for WF allocation, transmission expansion planning, and congestion mitigation planning based on a nodal price approach. The GGOD minimizes construction costs through suitable expansion planning functions and conducts effective congestion planning using its operational planning functions.

II. Expandable Micro-Grid Cluster

In this section, the concept and characteristics of the EMGC are explained.

The GGOD supports optimal design and operation. The EMGC concept is shown in Fig. 1. The EMGC contains micro-grids and transmission networks that are in-grid connected. The characteristics of EMGCs are as follows:

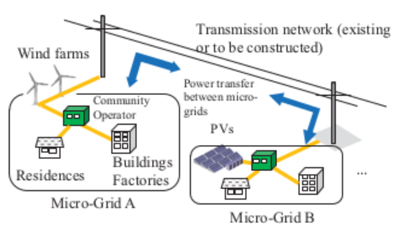

Fig. 1. EMGC concept.

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- In a micro-grid, properties for both power production and consumption are identified. In this way, local energy production–consumption information can be obtained.
- Power generation systems in EMGCs are mostly renewable energy sources. Therefore, the costs of introducing electricity are greatly reduced, in addition to the mitigation of greenhouse gas emissions.
- If micro-grids are either in excess of power or in need of more power, the micro-grids with a power surplus are able to transfer power to energy depleted micro-grids. Thus, the power balance is maintained among micro-grids.

III. Grid of Grids Optimal Designer

In this section, characteristic information of the GGOD is described.

A. Characteristics of the GGOD

The GGOD is a type of simulation software created to optimize the operational efficiency of EMGCs. The characteristics of the GGOD are as follows:

- *Optimizing long-term facility expansion planning*. Simulating investment in facility expansion allows for the price point of power transmissions to be optimized for long-term planning.
- *Integrating planning tools*. The GGOD provides integrated tools for planning resource expansion, transaction operation, and investment. These functions are used collaboratively.
- *Geospatial planning*. Geospatial data representing real world locations can be managed. Long-term facility expansion planning can therefore be executed on the geospatial platform termed the geographic information system.

For long-term planning tools, the Hybrid Optimization of Multiple Energy Resources [5] and Livelihood, Early Assessment and Protection [6] software are well known. These optimization tools, however, do not manage nor analyze geospatial data. Alternatively, the GGOD provides information on land conditions.

B. Functions and Data in the GGOD

The GGOD functions in Fig. 2 are classified into two .different types; planning functions for facility expansion and simulation functions for operational effects. The contents of these functions are as follows:

1) *Planning functions for facility expansions*:

- *Renewable energy generation expansion planning*. Site options for renewable energy production are extracted.
- *Transmission expansion planning*. Route designs for power transmissions are calculated.
- *Micro-grid cluster modeling*. Optimized facilities within a designated revenue are introduced.

2) *Simulating functions to estimate operational effects*:

- *Investment and pricing*. On the basis of demands, optimal investment strategies can be planned. When congestion occurs, power generation costs at two micro-grids are calculated on the basis of a nodal price approach.
- *Contingency analysis*. The contingency analysis function calculates the risks associated with serious disasters such as floods and output reconfigurations along power transmission routes for potential power transfer.
- *Micro-grid operational modeling*. Operating power supplies generated by cogeneration units, such as fuel cell batteries, are simulated, which can optimize power consumption.

When pricing is considered, contingency power supplies and power transfers within micro-grids are calculated. Power flows onto transmission networks are also examined. Power flows might include uncertainties since renewable energy such as wind and solar power are strongly dependent on weather conditions. For this reason, a stochastic power flow is calculated [7].

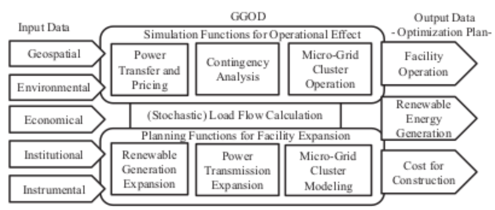

Fig. 2. Input to output structure of GGOD

Data managed and analyzed in the GGOD consist of five categories. Geographical, environmental, and economic data are all used to identify constraints for constructions. These data are explained in section IV for cost surfaces. Institutional data specify the required regulations and operational roles. Instrumental data define the types of facilities.

The data flow into the GGOD is shown in Fig. 3. The feedback process is also included as an important feature of the data flow. Operational simulations typically follow expansion planning. The GGOD iterates these processes and generates optimal results for both expansion and operational planning.

IV. Three-Dimensional Cost Surface and Zoning

A primary feature of the GGOD is that it manages and analyzes geospatial data. The geospatial data can be used to determine the feasibility of renewable power generation in a certain area, known as zone, and can be a reference for constraints in transmission expansions. The requirements for geospatial data are as follows:

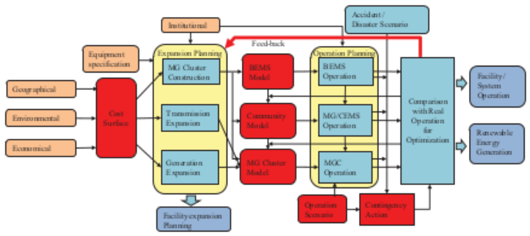

Fig. 3. Data flow into the GGOD.

- Possible zones where WFs exist, be distributed in large areas. For each area, the constraint conditions would be different. Therefore, location dependent conditions should be considered.
- Transmission networks operate in terrain areas. When determining appropriate transmission line routes, real topographical and environmental conditions need to be worked into the network length and construction costs. As transmission lines grow in length, a concern over power loss becomes important. Power losses change the total gathering power.

A. *Factors Effecting the Cost Surfaces*

The cost surface consists of three factors:

- *Geographical factors.* Constraints to a facility's construction may become an issue for topographical conditions such as height, slope angle, sky clearance angle, and construction restricted areas such as lakes and golf fields.
- *Environmental factors*. Construction restricted areas such as nature preservation areas, national park, and residence vicinities may become an issue.
- *Economic factors*. Costs for construction material transfers and power losses may affect transmission operations.

An example of the cost surface is shown in Fig. 4. The digital elevation model (DEM) is used as a base map. The DEM is a uniform-sized mesh data where height data are attached to the center of each mesh. Cost surface factors are overlaid onto the base map and represented three dimensionally.

B. *Zoning Maps as WF Feasible Areas*

WF feasible areas are chosen on the basis of wind speed. The constraints to the cost surface factors are as follows:

- Wind speed data, which have been calculated by computational fluid dynamics combined with wind speed measurements, are assigned on 500 m of mesh in the DEM. The DEM mesh, where the average yearly wind speed is bigger than 6.5 m/sec, is selected for candidates of WF feasible areas.
- When a DEM mesh is in a prohibited area, such as a national park, these meshes are excluded from the selection.

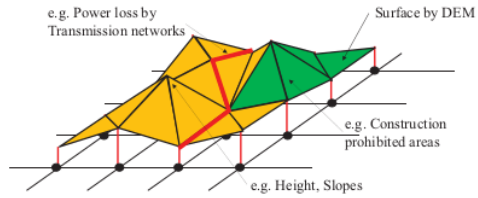

Fig. 4. Three-dimensional cost surface.

The resulting WF feasible areas are shown on the zoning map in Fig. 5. Once chosen, WFs are grouped to obtain the largest power generation source, generally at 80 MW, where energy management can occur across multiple sites. The grouping process of WF feasible areas is as follows:

Step1. Selecting a seed mesh with the biggest wind speed.

A mesh whose wind speed is the largest among unselected meshes is employed.

Step2. Grouping WF feasible areas.

Meshes next to a grouped area are merged into one group. When the total capacity exceeds 80 MW, the grouping process stops and *Step1* is implemented again. When all meshes are selected and grouped, *Step3* is then implemented.

Step3. Smoothing group boundaries.

Small-tip meshes at group boundaries are smoothed by changing a group. The result is defined as grouped WF feasible areas. The grouped result is shown in Fig. 6. It can be seen that cost surface factors affect the selection of WF feasible areas.

Fig. 5. Extracted feasible areas

Fig. 6. Result for grouping

V. A Key Function I – Geospatial Integrated Resource Planning

In the next sections, two key functions, namely, geospatial integrated resource planning (GIRP) and techno-economical estimates of micro-grid operation, are explained.

A. *Problem Description for GIRP*

When an area in demand for energy is far from the main grid network, new power transmission networks should be constructed, especially in remote areas. To implement this, however, a large budget is necessary. Thus, the problem of selecting optimal WFs and configuring their transmission networks should be solved and is explained. Fig. 7 shows the potential transmission structure of a system. Here:

- The total capacity of WFs selected is larger than the target capacity selected.
- Selected WFs are connected by transmission networks, and terminals are APs of existing grid networks.
- Since WFs are distributed in a large area, transmission networks are newly configured in a terrain; therefore, construction costs of WFs and transmission networks should be minimized.

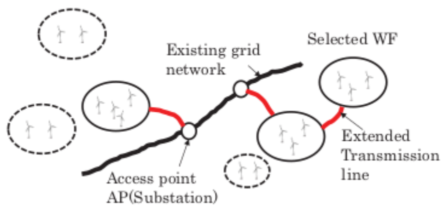

Fig. 7. Wind power transmission structure.

It can be expected that the WFs selected may affect the transmission network configurations. Thus, proposed planning is an integrated method for wind generation expansions and transmission expansions.

B. *The Optimization Process for Facility Expansion Planning*

The optimization process for facility expansions are as follows:

Step1. Finding of shortest route between a WF and an AP.

The shortest route is found automatically using the well-known Dijkstra algorithm by considering the cost surface conditions.

Step2. Optimizing WF selections and configuring transmission networks.

Transmission expansion planning is calculated by the optimization algorithm called the genetic algorithm (GA).

C. *The Objective Function for Optimization*

In this optimization procedure, the objective function and constraint conditions are defined. The objective function is defined as follows:

$$F = \sum_{i=1}^{N} W_i + \sum_{j,k(j\neq k)}^{M} T_{jk} + \sum_{m=1}^{L} S_m \qquad (1)$$

$$W_i = a_i F_i C_i \qquad (2)$$

$$T_{jk} = b_{jk} l_{jk}\left(t_{jk}(Y_{jk})\right) + \alpha_{jk} I_{jk} + \beta_{jk} H_{jk} + \delta_{jk} S_{jk} \qquad (3)$$

$$S_m = c_m T_m \qquad (4)$$

Where
Fi: Unit construction price of a WF (JPY/kW),
C_i: Generation capacity (kW),
l_{jk}: Transmission line length for interval (j,k) (km),
$t_{jk}(Y_{jk})$: Unit cost of transmission line construction, including labor and materials (JPY/km),
I_{jk}: Additional construction cost on sloping area (JPY/km),
H_{jk}: Additional construction cost on higher ground (JPY/km),
S_{jk}: Additional construction cost to allow for sky clearance (JPY/km),
T_m: Connection facility cost, including substations (JPY),
a_i, b_{jk}, c_m: = 1 selected, = 0 not selected.

The conditions to apply changes in I_{jk} H_{jk}, S_{jk} can be obtained from the cost surface at the locations in front of transmission networks.
The constraints are power balance at WFs and APs, as well as transmission capacity limits.

D. *Global Optimization by the Meta-heuristic Method*

For this optimization, a meta-heuristic method (the GA) is used. An outline of the GA is shown in Fig. 8.

The gene is defined for each WF. All WF genes are grouped as a chromosome. In the chromosome, when a gene is selected, this corresponds to a WF selection. The selection of genes in a chromosome is changed through GA processes. GA process consists of the selection, crossover, and mutation. The selection process prefers a chromosome with a lower objective function value. A crossover and a mutation are executed on chromosomes that are not selected for the selection process. Both a crossover and a mutation are probabilistic processes.

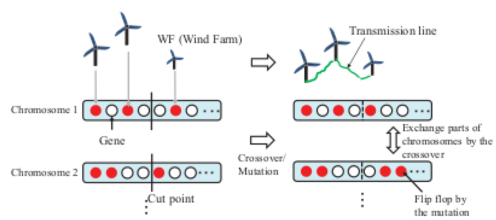

Fig. 8. Structure of the GA.

E. *Parameters and Simulation Results*

The simulation area chosen is in northern Japan. The simulation parameters are shown in TABLE I. In WF feasible areas, power aggregation points are set. Here, three cases are simulated, namely, (1) randomly selected points, (2) centroid points, and (3) points nearest to an AP in a group. For this simulation:

- The costs for constructing WFs and transmission networks are minimized for case (3).

TABLE I. PARAMETERS FOR PLANNING

Parameters	Value	Conditions
minimum introduced capacity	2.0 [GW]	-
WF construction cost	1.25[Million JPY/kW]	0.0~20.0 [GW]
	0.3[Million JPY/kW]	20.0~50.0[GW]
Transmission line construction cost	337 [Million JPY/km]	TACSR160 (386MVA)
	342 [Million JPY/km]	TACSR240 (509MVA)
	365 [Million JPY/km]	TACSR610 (912MVA)
Substation cost	100 [Million JPY/each]	constant
Altitude limit	1200 [m]	-
Slope angle limit	30°	-
Sky clearance limit	75°	-

- The total introduction power is set at 2.09 MW and comparable with target power 2.0 MW.

An image of the WF selections and the transmission network configurations for case (3) is shown in Fig. 9.

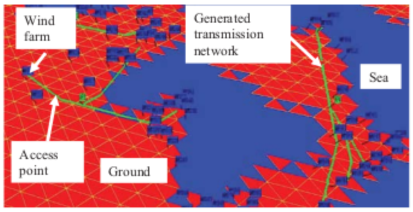

Fig. 9. The configuration of transmission networks.

VI. A KEY FUNCTION II – TECHNO-ECONOMICAL APPROACH OF CONGESTION MANAGEMENT

The GGOD includes a model for power transmission between EMGCs to determine the transmission price. A model with three micro-grid nodes is shown in Fig. 10.

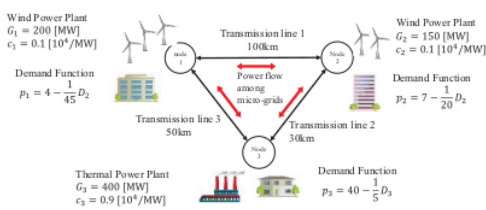

Fig. 10. Three node models for EMGC.

Considering a competitive market, the power supply function is ranked according to power generation availability, known as "merit-order." The optimum price is then forecasted at the intersection point of the demand function. In this situation, the price that maximizes social welfare is determined using the nodal price method [8].

A. Objective Function for Optimization

Equation (5) gives the objective function calculation for social welfare, where

$$S = \sum_{n=1}^{3}\left[\left(a_n D_n - \frac{1}{2} b_n D_n^2\right) - \sum_{i=1}^{3} c_i q_{ni}\right]. \quad (5)$$

a_n: A cross point y-segment value of an inverse demand function,
b_n: An inclination of inverse demand function,
D_n: A demand at a node,
c_i: Marginal cost of generation with generator i,
q_{ni}: Power supply from generator i to node n.

The power flow balance, capacity limits of transmission lines and generation facilities, and the fact that the power producers always earn nonnegative profit, are set as the constraints.

Transmission charges are determined on the basis of the nodal price. The price at each node is equal to the sum of the locational marginal price and the opportunity costs generated through transmission congestions. When actual congestion occurs in the transmission system, the amounts of generation and demand change are imposed on all nodes. As a result, the transmission charge becomes the difference in nodal pricing between two specified nodes.

B. Simulation Conditions and Results

Here, two cases are simulated:
Case 1. Where no congestion occurs and
Case 2. Where transmission congestion occurs at line 3 (Fig. 10).

The transmission capacities are listed in TABLE II and the resulting power flow and transmission charges are listed in TABLE III.

TABLE II. SIMULATION PARAMETERS FOR TRANSMISSION LINE CAPACITY

	K_1 (MW)	K_2 (MW)	K_3 (MW)
Case 1	100	100	100
Case 2	100	100	40

TABLE III. RESULTS OF THE POWER FLOW AND TRANSMISSION CHARGE

Case and Estimation item		line1	line2	line3
Case1	PF	12.139	40.139	48.361
	TC	0	0	0
Case2	PF	8.923	36.923	40.000
	TC	-0.61537	-0.18461	0.79999

PF: Power flow (MW), TF: Transmission charge ($\times 10^4$/MW)

In Case 1, the transmission charges at all nodes start at zero since no congestion occurs. In Case 2, the optimum price is found at the intersection between the inverse demand curve and the merit-order curve. All generation supplies are reduced to prevent congestion. In order to control the price at node 1 and the power flow in line 3, generation at node 1 is set below capacity. Thus, the difference between nodal prices increases.

VII. A PERSPECTIVE ON THE INTERRACTIVE USE OF FUNCTIONS THROUGH THE GGOD

The GGOD integrates two key functions as described in section V and VI. The interactive use of the two functions creates optimal results for both facility expansion planning and operational planning. Since demand changes and generated wind power contain uncertainties, even with optimal facility expansion planning, congestion may occur in some areas of the transmission network. Therefore, an iterative interaction process is used for both functions. The method is shown in Fig. 12 through a three-step process.

Step1. Selecting a WF and transmission networks.

The node that represents WFs, APs, and transmission networks (which connect WFs and APs) are selected in transmission expansion planning as detailed in section V.

*Step*2. Converting connections to a topology.

The topology is based on the connection structure, which is determined where WFs and transmission networks are located.

*Step*3. Investment and pricing analysis.

Here, grid network congestions are analyzed together with the feasibility of investment and pricing.

In this way, any unexpected events can be detected. The expected total power injection at an AP are fed back at the transmission expansion planning stage, with steps 1 to 3 are executed again.

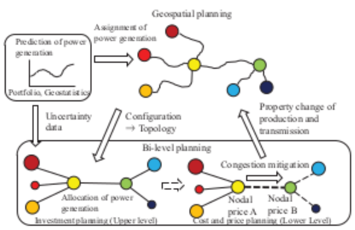

Figure 11. Interactive functions in the GGOD

VII. DISCUSSION

The method introduced here using the GGOD contributes to the long-term planning of renewable power. Here, three points of view, namely, the optimization functions, their integration, and use of geospatial data, are described.

1) Optimization functions.

- In large areas, renewables are distributed unevenly. Therefore, geospatial planning is used to select WFs and configure transmission lines since the construction costs depend on the spatial conditions represented by the cost surface.
- The optimization method, such as the GA, is effective for a large number of WF selections and transmission network configurations.

2) Integrated use of the functions.

- The introduction of geospatial facilities and techno-economical analyses can be connected effectively.
- A method is described for long-term planning. Here, planning tools based on geospatial processing would be the new type of platform.

3) Use of geospatial data.

- Since the GGOD integrates geospatial data, selecting practical areas to place renewable energy generators, zoning, and transmission networks can be executed.
- The cost surface plays an important role in extracting the feasible areas and configurations by considering real world conditions.
- The proposed method uses geospatial expansion of integrated resource planning [9].

VIII. CONCLUSION

In this paper, the optimal design suite called the GGOD is proposed. Characteristics of the GGOD are (1) optimization tools for long-term facility introduction planning and operation planning, (2) assisted integrated resource planning, and (3) use of geospatial data.

The conclusions are as follows:

- The GGOD is an optimization platform for the introduction of facility planning and operation planning. These functions will be interactively used.
- Zoning maps and cost surfaces are used to extract WF feasible areas and transmission network configurations.
- Each function attached to the GGOD is interactively used with the results optimized for facility introductions and their effective uses.

In future work, the interactive use of the functions described will be verified in South-East Asian counties.

ACKNOWLEDGMENT

This research was supported by the Japan Science and Technology Agency, the National Science and Technology Development Agency of Thailand, and the Department of Science and Technology of The Philippines as part of the e-ASIA Joint Research Program (e-ASIA).

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