Energy Network Optimal Control Technology

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Abstract

Distributed energy is a concept in which many low- to mid-capacity power generation sources such as fuel cells and solar cells are concentrated in a certain area, and close attention has been focused on using a communications network to achieve optimal control of a distributed energy network supplying electricity and heat. This paper discusses optimal scheduling technology needed to implement energy network control and describes an actual pilot implementation of the technology at Expo 2005 in Aichi Japan.

1. Introduction

Demand for energy has continued to rise in recent years, and the increasing use of energy has been accompanied by increasing CO_2 emissions. One way of reducing or at least curtailing the growth of CO_2 emissions is to stop relying on only centralized high-capacity power plants and to introduce distributed energy systems based on smaller-capacity power generation sources such as fuel cells and solar cells. Distributed energy has a number of compelling advantages: energy savings (from improved energy use efficiency through the cogeneration of electricity and heat), lower environmental impact (from cleaner energy), and greater economic efficiency (from reduced energy costs through more efficient control of operations).

By combining environmentally friendly distributed energy with the ability to monitor and control distributed energy sources in a concentrated area via a communications network, we could implement a highly reliable energy network with excellent availability, such as illustrated in **Fig. 1** which can deliver electricity within a district in a flexible manner. The conventional technology for operating a cogeneration system is only able to take into consideration simple system characteristics, but we need to consider various complex characteristics on the energy network, so we require technology that can control a lot of distributed energy.

2. Optimal control of the energy network

Actual deployment of an economical and environmentally friendly energy network requires control technology that senses the efficiency and operating constraints of each piece of equipment in the distributed energy system and runs the equipment optimally. Most important is a precise operating schedule specifying when to use different power generation sources. Without such a schedule, a considerable load would be imposed on the distributed energy equipment due to sudden changes in fuel cells, excess charging and discharging of batteries, and so on, which could lead to the loss of the potential environmental and economic benefits. In addition, distributed energy sources based on natural energy, such as solar- and wind-generated power, are greatly affected by climate and weather conditions. Environmental and economic benefits could be markedly improved if we could accurately estimate the demand for electricity and heat in addition to estimating the amount of power that can be generated by sunlight and wind and then determine the operating schedule according-

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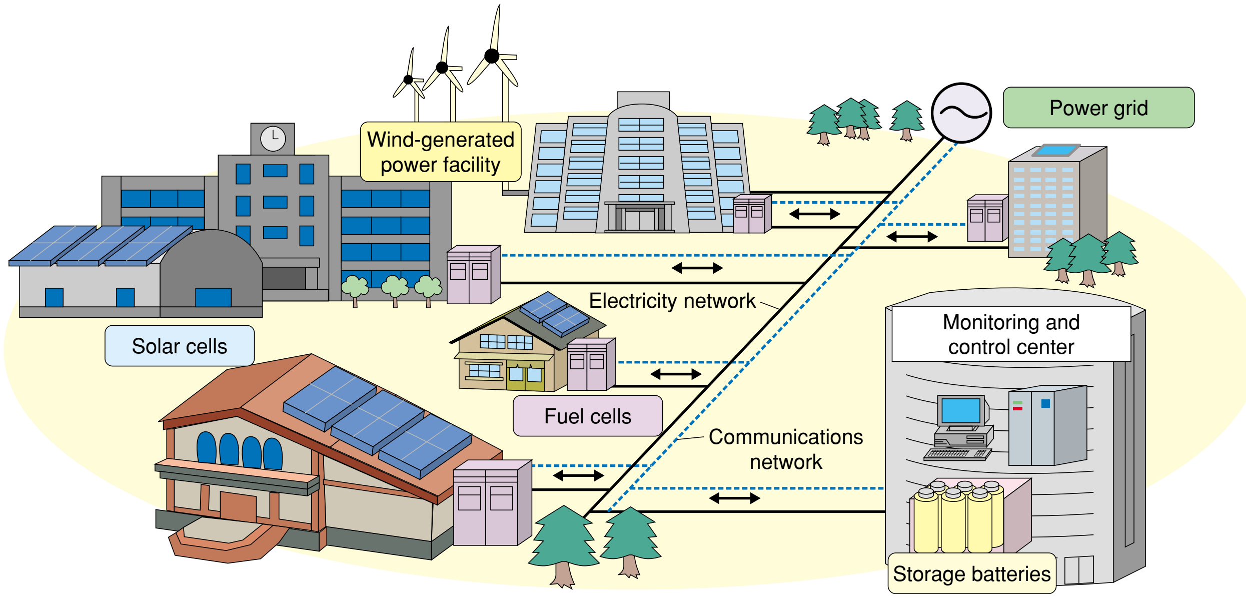

Fig. 1. Schematic overview of energy network.

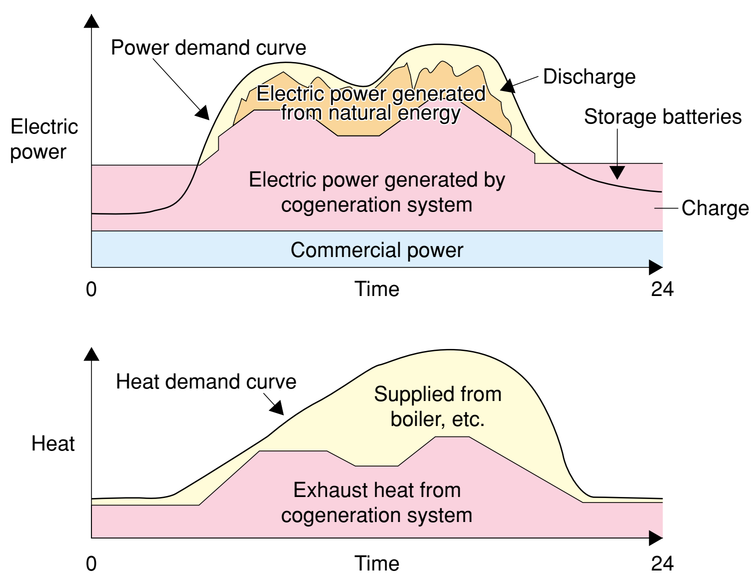

Fig. 2. Schematic of energy demand and optimal energy control.

ly. We could also achieve much more efficient control over the energy network as a whole if we could reduce fluctuations and equalize loads by temporarily storing energy in storage devices (e.g., batteries).

A schematic representation of energy demand and optimal energy control is shown in **Fig. 2**. Demand for energy covers both electricity and heat, so the various distributed energy sources should be scheduled in such a way as to optimize total energy. Here, excess electricity is stored in storage batteries and discharged as needed. This means that a balance must be achieved, say over a one-day period, so the amounts of energy stored and discharged are approximately equal. This same kind of balancing must also be considered in the case of heat, which is stored in a heat storage device.

A simplified energy control flow chart is shown in **Fig. 3**. Projected temperature and weather conditions for the next day are obtained from the weather forecast. This information is then combined with past performance data to estimate both the amount of electricity and heat that can be generated sources of natural energy and the demand for electricity and heat. These estimates are then used together with the various distributed energy characteristics and operating constraints that can be controlled to determine the optimal distributed energy power generation scheduling that will minimize CO_2 emissions or energy costs over a one-day or several-day period. This optimized operating schedule is then used to control the distributed energy system.

The power supply or demand estimates will sometimes be wrong because the weather forecast was wrong or for some other reasons. To cope sudden unexpected demands, we need a way to correct the disparity between planned values and actual required values. This can be done using a realtime balancing control that synchronizes the total demand and the total supply within a fixed period. In addition, the estimates are periodically updated and revised to reflect the actual energy storage situation, so it is also necessary to repeatedly recalculate the optimal scheduling. This means that the optimal scheduling must be calculated quickly.

A number of these technologies are required to implement optimal control of energy networks. All of these technologies are now under development. The rest of this article focuses on the optimal scheduling technology.

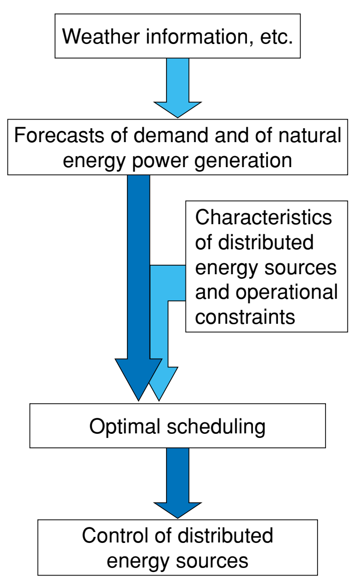

Fig. 3. Energy control flow.

3. Optimal scheduling using meta-heuristics

Distributed energy optimal scheduling involves trying to derive the best combination of the outputs of different energy sources to meet a particular objective, such as low CO_2 emissions, low energy cost, or high efficiency, while distributed energy operation constraints represent a constrained optimization problem. The manner in which solutions to optimization problems are found is schematically illustrated in **Fig. 4**. The search space is a complex multi-dimensional space in which search path options are reduced by constraints (Fig. 4(a)). The number of dimensions is the product of the number of distributed energy sources and the number of time periods. For example, in scheduling ten distributed energy sources to operate in one-hour scheduling periods, we need an extremely large space with 240 dimensions. The objective is to discover the point where the score of the operating schedule (the solution) is best within that search range. The search process is illustrated in Fig. 4(b), which shows four kinds of search process-

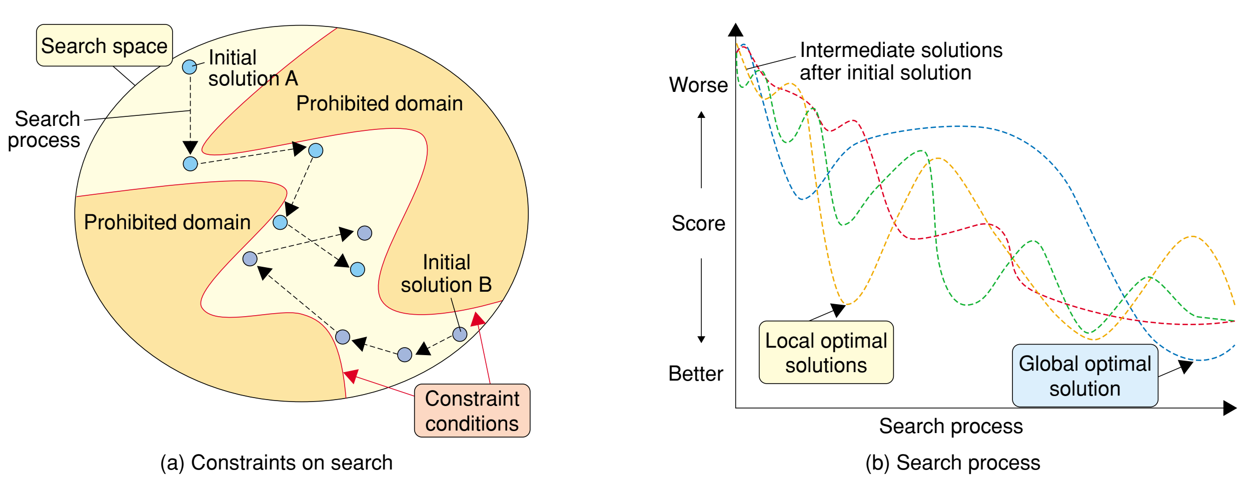

Fig. 4. Schematic representation of optimization problem solution search.

es as examples. Points that have the best score within a limited range are called local optimal solutions. After the entire space has been searched for solutions with relatively good scores, the problem becomes one of choosing the global optimal solution.

Mathematical programming that was used extensively in the past for power generation scheduling has a number of shortcomings when applied to distributed energy systems. It requires an inordinate calculation time due to the nonlinear and discontinuous nature of distributed energy sources, and it can only produce local optimal solutions. Consequently, this conventional approach is used to determine only operating schedules in which the efficiency requirements and other conditions are fairly simple.

Meta-heuristics [1] are uniform methodologies based on heuristics testing for efficiently finding solutions to optimization problems. They can obtain highly accurate approximate solutions to global optimization problems quite quickly regardless of the type of evaluation function or constraints. By adroitly applying this method, we implemented a scheduling scheme that is not affected by the characteristics of complex new energy equipment or systems or other constraints.

A wide range of meta-heuristics have been proposed and investigated. For our application, we considered two representative ones: the genetic algorithm, which is a useful technique for global searches, and the tabu search, an excellent local search procedure. Let us consider these methods in greater detail.

(1) Genetic algorithm

The genetic algorithm [2] is a particular class of evolutionary algorithms that use techniques inspired by evolutionary biology for engineering modeling. In biological evolution, multiple entities form a population, and those entities that are best adapted to the environment are selected (like the process of natural selection) and tend to survive. The fitnesses of multiple entities (operating schedules) are calculated using an evaluation function. Then, the entities are manipulated by genetic operators—selection, crossover, and mutation—and the ones having better fitness (i.e., ones that are better solutions to the problem) survive and propagate to the next generation. This process is repeated for subsequent generations until the entity (operating schedule) with the best fit among all the generations remains as the optimal solution. A genetic algorithm search yields multiple points (entities), so it is suitable for a global search.

(2) Tabu search

The Tabu search [3], [4] is an optimization method that is analogous to the human memory process. While avoiding cycling through the same solutions (operating schedules), the tabu search moves toward better scores (or when tending toward worse scores, it moves in the direction in which the slope is most gradual) relying on memory structures. To avoid going back to solutions that have already been traversed, it stores in memory a *tabu list* containing the names of those solutions. Going back to the same solution or moving to similar solutions is forbidden, so the tabu search can escape from local optimality to find a global optimal solution.

Even if the application of these two methods is not ideal, one can sometimes derive the optimal solution with just a local search. In genetic algorithms the genetic coding scheme and procedures for adjusting the various parameters are difficult, while in tabu searches defining the neighborhood and storing attributes in memory are problematic. By devising an application method that permits a global search that is stable even when various conditions are involved, we have obtained a scheduling algorithm that is both flexible and highly general.

4. Demonstration at Expo 2005, Aichi Japan

The New Energy and Industrial Technology Development Organization (NEDO, an independent administrative agency) commissioned the world's first trial implementation of a large-scale new energy system to supply electricity and heat to the Japan Government Pavilion and other facilities at Expo 2005, Aichi Japan. NTT Facilities, Inc. was put in charge of developing the energy control system, and they commissioned us to develop the optimal scheduling system [5].

NTT Energy and Environment Systems Laboratories developed a program that forecasts output from photovoltaic power sources and features the two types of optimization algorithms described above for optimizing energy source scheduling. Since genetic algorithms are particularly useful for global searches, we concentrated on programs emphasizing speed. On the other hand, to exploit the full potential of the precision of tabu searches, we adjusted parameters to achieve precise optimizations. In demonstration research performed at the Expo, we used the results of solar-generated power forecasting to calculate the optimal scheduling of various energy sources and then performed a comparative assessment of the

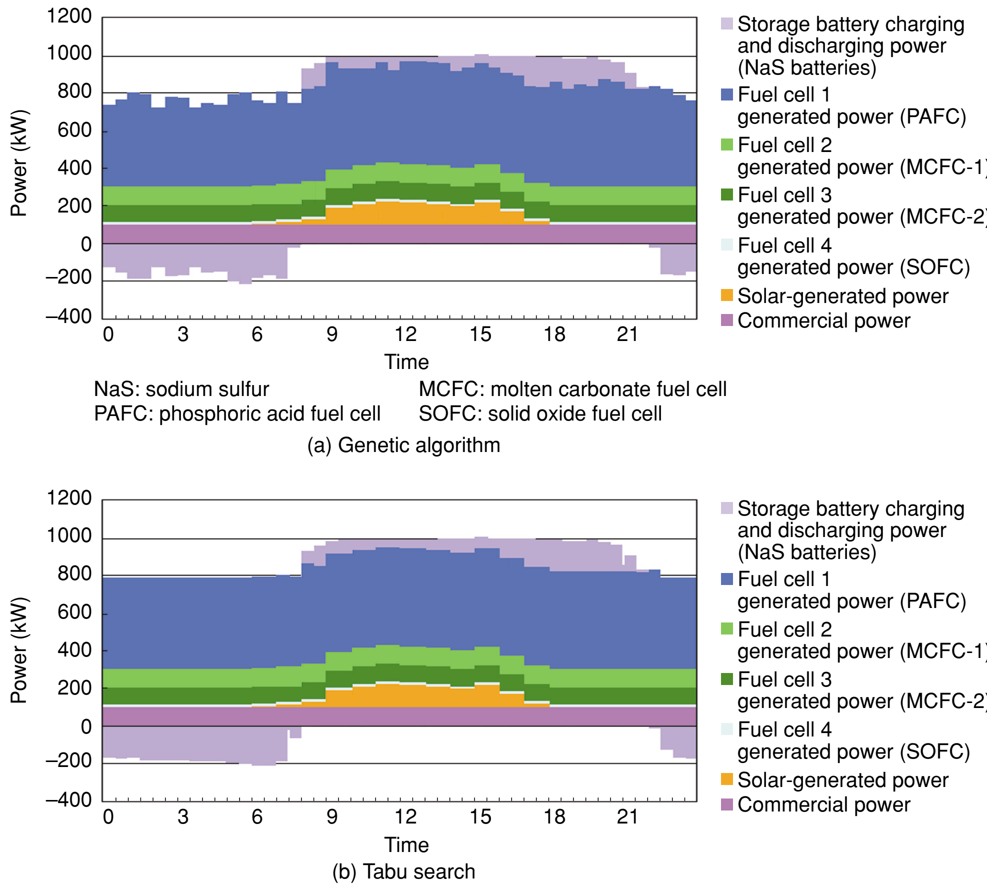

Fig. 5. Example of optimal scheduling for actual operation.

results of applying the genetic algorithm and the tabu search.

The results confirmed that the pilot implementation met the performance targets. The optimal scheduling results are summarized in **Fig. 5**. The genetic algorithm proved very effective in calculating approximate solutions with a sufficient degree of accuracy within a short period of time (about one-tenth the time of the tabu search). The tabu search output stable and very accurate optimal solutions, while calculating smooth time-series operating schedules that should not shorten the lifetime of fuel cells.

5. Future research

Close consideration of environmental impact will become more important as time goes on, and we will see more implementations of distributed energy systems in the future. Following up on these promising results, we plan to develop optimal scheduling technologies that can deal quickly and accurately with all the complex characteristics and constraints of new energy equipment.

Acknowledgments

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