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研究課題名（和文）Study of Intelligent and Secure Smart Grid Infrastructure With Effective Eco-Friendly Power Distribution Techniques

研究課題名（英文）Study of Intelligent and Secure Smart Grid Infrastructure With Effective Eco-Friendly Power Distribution Techniques

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研究成果の概要（和文）：本研究ではスマートグリッドに関する研究の一環として，特にマイクログリッドシステムにおける分散制御方式の提案を行った．具体的には，各マイクログリッドの協調動作における各種制御パラメータの検討に取り組み，アルゴリズムの構築を行った．これにより，効率的なシステムの協調動作を実現し，電力損失の削減を達成した．
また，上記に挙げた研究成果を社会に向けて発信していくため，成果についてまとめ，著書１件，その他複数の論文誌並びに国際学会発表論文を執筆している．

研究成果の概要（英文）：Since power generation of renewable resources are not stable and customer-demands are usually time-varying, the supply power and demands of the customers are always unequal. Hence, we designed a smart grid architecture and included micro-grids with storage equipment to satisfy the demands of the customers. Adequate communication frameworks were developed also. Our studies analyzed high power loss issues when power is transmitted from primary power generation to secondary power generation sources, and also among micro grids. First, a centralized solution to optimally solve the problem was proposed. By taking the result of the centralized solution as "baseline", a distributed solution was then formulated and evaluated with effective performance.

In this topic, several journals, a conference paper, and a complete book has been published in the three fiscal years.

研究分野：Smart grid

キーワード：Communication　Information Technology　Smart grid

１．Research background (研究開始当初の背景)

The smart grid concept is synonymous to intelligent grid or future grid, and is aimed at providing the end-users with more stable and reliable power. The common aspect of the different smart grid proposals consists in the two-way communication framework between the power source and the consumers, and intelligent sensing entities and control systems lie along the path of the power source and the end-users. The sensors have the ability to detect malfunctions or deviations from normal operational trends which usually require appropriate responses from the smart grid control center. Furthermore, the responses from the control center need to be converted into appropriate control messages and transmitted to different segments of the smart grid.

The renewable electricity generation and delivery is an important aspect of the smart grid. Micro grids (smaller autonomous power generation and dissemination systems) which could be connected and isolated from the main power grid are becoming more common. The micro grids are perceived as the means to reduce unnecessary/fossil-based power generation and distribution, and reduce the total power loss across the main grid. The echo-friendly or ``green" micro grids are, therefore, gaining lots of attention from the mainstream smart grid community.

The review of available micro grid architectures showed that most of the existing testbeds are AC (alternating current) micro grids because they are easy to integrate with the main power grid and most loads (user appliances) which run on AC. The AC micro grids, however, struggle with maintaining a stable power quality. This is one of the critical shortcomings of the AC micro grids. In contrast, the DC (direct current) systems in general are not prone to power quality problems. But deploying the DC micro grid is not practiced much due to limited use of DC loads by the customers. HFAC (high frequency AC) micro grids are now gaining popularity that can help integrating renewable energy sources with the micro grid while maintaining a reasonable power quality. A HFAC micro grid system has its own disadvantage, however. It usually needs more control devices, and suffers from a large voltage drop and long distance power loss. The conventional power generation source of the micro grids is typically diesel; but renewable sources like solar power volt, wind, and micro-hydro systems are becoming popular deployment choice for the micro grids. Because the renewable sources are highly dependent on the ambient environment, the micro grid usually is deployed with power storage devices to store power for later use. Most existing test-beds have battery storage while some have capacitor banks and flywheels as storage devices. Several storage units are deployed in some micro grids while others do not have any storage unit at all. If the micro grid system does not have any storage device and only have renewable energy source, then the main grid connectivity is a very important option for that micro grid system. There is definitely room for further study on the deployment scenarios of the micro grids.

To demonstrate that micro grids are not merely research projects, let us consider the example of a major aversion of power outage by exploiting a micro grid using renewable sources in late May 2015. The Borrego Springs micro grid supplied energy to 2,800 customers for nine hours until the utility operator (San Diego Gas & Electric) repaired the damage inflicted by a lightning strike. The micro grid automatically switched between its different power generation sources like onsite energy, energy storage, and a 26MW solar generation source to steadily manage power supply to the customers of the entire community. This shows the immense potential of micro grids in days to come.

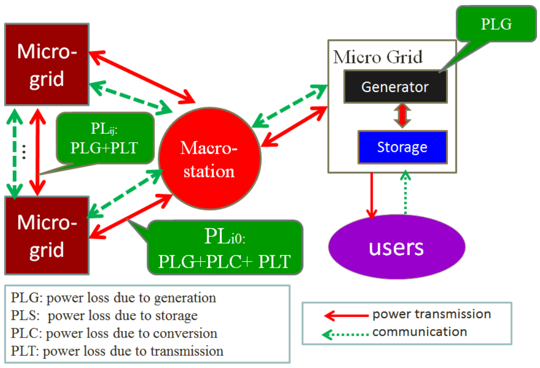

Figure 1. Designing a model of micro grids with power losses minimization objective.

２．Research Objective (研究の目的)

When we deal with a large number of micro grids, substantial reduction in power loss may be impossible without optimizing the scheduling of local energy generation and distribution of the micro grids. In addition, the micro grids could have local storage facilities to locally store energy for selling to their own customers or even other micro grids at a later time. Should we consider the power generation and storage losses also in addition to the distribution loss? In addition, how to deal with such problems? In other words, who will decide the schedule of generation and storage? A centralized decision maker certainly sounds interesting, but may not be as impressive in real-time compared to a distributed decision making solution. The research objective of this project is to formulate both centralized and distributed solutions to minimize power loss across the micro grids and the macro station.

３．Research Methods (研究の方法)

Even though a significant progress has been achieved in the development of the micro grids, the power loss minimization between the micro grids and also between the macro station and an individual micro grid are still receiving much attention. Previously some researchers considered an algorithm aimed to optimize the transmission strategy in order to minimize the total cost including the power loss. The power losses minimization in the energy distribution networks has conventionally been investigated using a single and deterministic demand level. The “cost-aware smart micro grid network design” allows economic power transactions within the smart grid with manageable power losses. Also there exists some works discussing power loss minimization issues by proposing a coordinated control scheme at real-time with the inclusion of distributed generation resources (micro grids) with the existing grid. A novel load management solution to coordinate the charging of multiple PHEVs in a smart grid system was also considered in some interesting works. Compared to the existing studies addressing the power loss minimization problem of distribution networks in a scattered manner, we understood the need to have a more comprehensive insight into this issue in the micro grids context. First, we designed a basic micro grids system model and illustrate how formulation of effective coalitions between the micro grids can be useful in significantly reducing the distribution power loss.

Figure 1 shows our considered system model comprising a number of micro grids. This model considers that the users are supplied electricity by the macro station and/or a number of autonomous micro grids using distributed, renewable energy sources like wind farms, solar panels, PHEV batteries, etc. Each micro grid is linked to the macro station through the main power grid. Also, each micro grid is assumed to have its own customers such as residential users, schools, factories, etc, who have the capability to notify their respective micro grid(s) regarding energy demands via AMI. Because the power loss between the macro station and the micro grid is usually more than that between two neighboring micro grids, the adjacent micro grids could potentially improve the power loss through forming supportive groups, which we refer to as coalitions. A coalition can initially form with just one micro grid.

Now we consider the cooperative coalition model for managing the micro grids acting as buyers and sellers. In addition to exchanging energy with the macro station, the micro grids are able to exchange energy with each other. This is particularly attractive to the micro grids because the power loss during transmission between the neighboring micro grids is always less than that between the macro station and a distant micro grid. Furthermore, the micro grids can make collaborative groups or coalitions as explained earlier to exchange energy with each other so as to minimize the power loss in the main smart grid and maximize their payoffs.

First, we excluded the power storage devices for a simple scenario. Then we used game theory for making an optimal coalition formation algorithm among the micro grids to solve the power minimization problem.

The algorithm allows merge and split operations through which the micro grids can join and leave the coalitions in a dynamic way depending on their current energy demand or surplus, respectively.

The next step was to incorporate storage devices in the micro grid model (i.e., we fully realized the model of figure 2). Gradually building the model allowed us to understand how different elements in the model led to different interactions influencing the power loss. When power storage devices are taken into account, power storage losses such as in PHEV batteries become a key problem. This problem was overcome by designing a superior game theoretic coalition formation algorithm of the micro grids.

Finally the importance of a decentralized or distributed method for minimizing the power losses was stressed upon. The centralized models are taken as baseline models and a distributed solution is developed. Of course the performance of the distributed solution whereby the micro grids cooperate with their immediate neighbors (e.g., 1-hop neighboring micro grids) only to minimize their power losses. Problem of this approach is that each micro grid has partial information of the whole smart grid, and each trying to minimize the power losses according to its own knowledge was a difficult proposition. Nevertheless we used game-theoretical interactions of the micro grids to reach a distributed consensus which approaches the optimal baseline performance.

4. Research Results（研究成果）

The micro grid power minimization study through a basic centralized approach, a more complex centralized method, and then a distributed approach are the three core technologies developed in course of this project. The technologies had to be gradually/sequentially developed since understanding the research result or system performance of each stage gave crucial idea on how to develop the subsequent research phase.

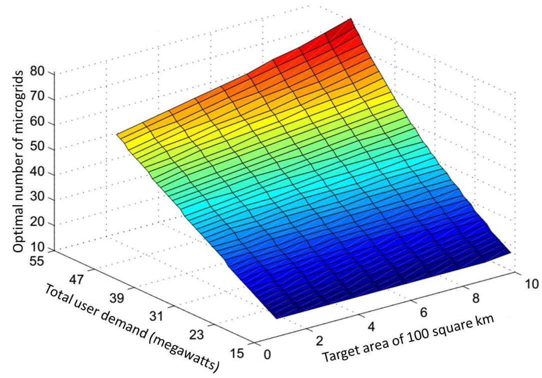

Figure 2. Optimal number of micro grids

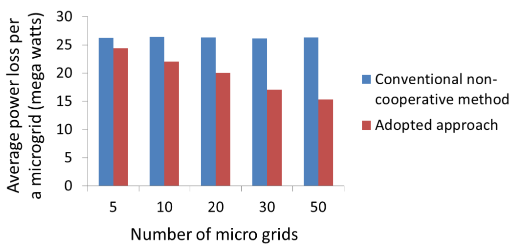

Figure 3. Average power loss per micro grid in existing and proposed (adopted) approaches

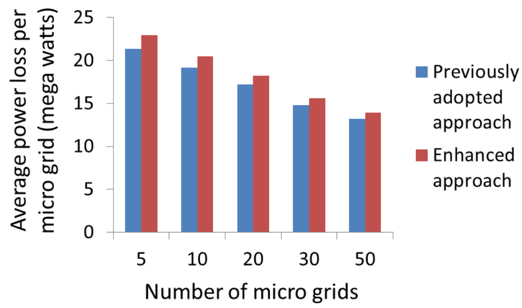

Figure 4. Comparison of average power loss per micro grid in proposed centralized (previously adopted) and decentralized (enhanced) approaches

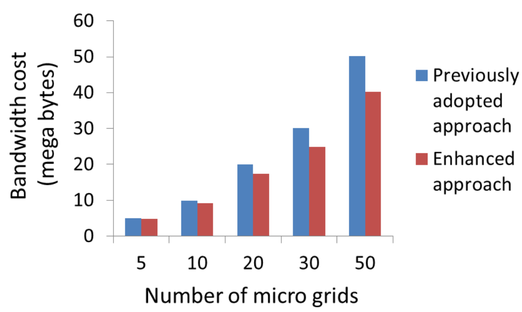

Figure 5. Comparison of bandwidth per micro grid in centralized and decentralized (enhanced) approaches

(1) Research Summary of 2013
(平成 25 年度の成果概要)

Our adopted approach is compared with the non-cooperative case and also a conventional algorithm called NMS which are referred to as conventional1 and conventional2, respectively. When the number of micro grids increases, the average power loss changes just a little in the non-cooperative conventional1 case. On the other hand, in case of conventional2 and the adopted approach, the power losses decrease with the growing numbers of micro grids. When the number of micro grids is 50, the power loss in the adopted approach reaches up to significant reduction compared to conventional2 approach. This superior performance happens because the power losses within the formed coalitions in the adopted approach are much lower than those between the macro station and the micro grids. As a result, when most of the micro grids have joined coalitions, the overall cost of the users decreases, and thus, the adopted approach outperforms conventional2 in terms of improvement of the average power loss. To reflect the money saving of the users, Figure 2 demonstrates the optimal number of micro grids in different cases. Remember that the optimal number of micro grids depends on the area of the considered area and the demands of users in that area. Therefore, with increasing demands, the users require more electricity from the micro grids to reduce their cost (compared to procuring electricity from the macro station). For instance, the optimal number changes from 15 to 50 when the demands changes from 15 MW to 55 MW in the the considered grid area of 10 × 10 km 2 . Furthermore, because the resistance is a linear increasing function of distance, a higher resistance means a higher power loss. So, in a larger area, more micro grids want to minimize the higher power loss. Although not shown in the figure, as the area changes from 100 km 2 to 1000 km 2 and the demands are 15 MW, the optimal number of micro grids to form coalitions becomes from 15 to 17.

(2) Research Summary of 2014
(平成 26 年度の成果概要)

Figure 3 shows the average power loss per micro grid for different numbers of the micro-grids ranging from 5 to 50. In the conventional method, the power loss per micro grid does not improve since the micro grids only obtain power from the macro station. On the other hand, in case of the proposed approach, the average power loss is significantly improved with the increasing numbers of the micro grids. This happens because the coalitions are formed by the micro grids with the objective of optimally alleviating the power loss. When the micro-grids could successfully make the coalitions in the adopted approach, they could exchange power with other micro grids instead of the macro station leading to the reduction of the average power loss.

(3) Research Summary of 2015
(平成 27 年度の成果概要)

Figure 4 shows that the average power loss in the distributed approach is slightly higher than that in the centralized approach. On the other hand, because the micro grids do not send information to the control center, the communication bandwidth cost in the distributed approach is lower than that in the centralized approach as demonstrated in Figure 5. It means that by using the distributed approach, precious communication bandwidth could be saved for more important tasks such as accommodating many more customers the critical AMI-oriented communication in the micro grids.

(4) Technical summary (技術の概要)

In the work, we developed novel cooperative power exchange algorithms for micro grids from both centralized and distributed perspective. These allow the micro grids to form coalitions so as to minimize the total power loss. Through numerical results, the effectiveness of the approach was verified. Comparative results showed its superior performance compared to a conventional distributed method. Also, some trade-off in the performance between the centralized approach and this distributed one could be seen.

５．Main Publications etc (主な発表論文等)

[Journal (Peer-reviewed)]
〔雑誌論文(査読付き)〕（計 3 件）

1. Chao Wei, Zubair Md. Fadlullah, Nei Kato and Akira Takeuchi, "GT-CFS: A Game Theoretic Coalition Formulation Strategy for Reducing Power Loss in Micro Grids," IEEE Transactions on Parallel and Distributed Systems, vol. 25, no. 9, pp. 2307-2317, Sep. 2014.
2. Chao Wei, Zubair Md. Fadlullah, Nei Kato, and Ivan Stojmenovic, "On Optimally Reducing Power Loss in Micro-Grids with Power Storage Devices," IEEE Journal on Selected Areas in Communications (JSAC), vol. 32, no. 7, pp. 1361-1370, Jul. 2014.
3. Z. M. Fadlullah, D. M. Quan, N. Kato, and I. Stojmenovic, "GTES: An Optimized Game-Theoretic Demand-Side Management Scheme for Smart Grid," IEEE Systems Journal, vol. 8, no. 2, pp. 588-597, Jun. 2014.

[Conference (Peer-reviewed)]
〔学会発表(査読付き)〕（計 1 件）

1. Wei Chao, Zubair Md. Fadlullah, Nei Kato, and Ivan Stojmenovic, "A Novel Distributed Algorithm for Power Loss Minimizing in Smart Grid," 2014 IEEE International Conference on Smart Grid Communications, Venice, Italy, Nov. 2014.

[Book]
〔図書〕（計 1 件）

1. Zubair Md. Fadlullah and Nei Kato, "Evolution of Smart Grids,"SpringerBriefs in Electrical and Computer Engineering, SpringerInternational Publishing, Dec. 2015.(ISBN 978-3-319-25391-6)

〔その他〕
(1)ホームページ
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６．研究組織

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