博士学位論文審査要旨

２０１６年8月３０日

論文題目： Conceptual study on the energy independence of fuel cell cogeneration systems using solar energy
（燃料電池及び太陽光エネルギーを利用するシステムのエネルギー自立性に関する研究）

学位申請者： Lamas De Anda Jorge Eduardo

審査委員：

主　査：　同志社大学大学院理工学研究科　教授　　千田　二郎
副　査：　同志社大学大学院理工学研究科　教授　　平田　勝哉
副　査：　同志社大学大学院理工学研究科　准教授　松村　恵理子

要　　旨：

有限な化石系資源の長期的利用および地球温暖化防止のためには、再生可能ｴﾈﾙｷﾞｰ利用の最大化、大規模集中型ｴﾈﾙｷﾞｰ供給形態（ﾊｰﾄﾞﾊﾟｽｸﾞﾘｯﾄﾞ）から都市部や居住区での小型・分散型ｴﾈﾙｷﾞｰ供給形態への移行、さらに高いｴﾈﾙｷﾞｰ効率を有するｺ･ｼﾞｪﾈﾚｰｼｮﾝ（ｺｼﾞｪﾈ）の利用が必要である。

本論文は、太陽光発電（ＰＶ）より製造した水素を燃料電池（ＦＣ）に供給して都市部・居住区のｿﾌﾄﾊﾟｽｸﾞﾘｯﾄﾞのｴﾈﾙｷﾞｰ自立性の向上を解析的に明らかにしたものである。論文は８章から構成されている。第１章は本研究の背景および目的について述べている。第２章では、再生可能ｴﾈﾙｷﾞｰ、燃料電池およびｴﾈﾙｷﾞｰ貯蔵装置などの分散型ｴﾈﾙｷﾞｰｼｽﾃﾑの特質を概説している。第３章では本研究で対象とするＰＶとＦＣから構成されるｺﾝﾊﾞｲﾝﾄﾞｼｽﾃﾑの詳細とＦＣに水素を添加した場合の作動特性結果を示し、第４章ではｼｽﾃﾑの最適運用の手法を解説している。第５章では本ｼｽﾃﾑを最適に運用した場合の水素消費量とｴﾈﾙｷﾞｰ低減量の解析結果を定量的に示し、さらに第６章では本ｼｽﾃﾑでの水素供給経路の影響をモデル解析し、第７章では具体的な適用事例を紹介している。このように、本論文では実験的研究として居住区での固体酸化物型燃料電池に都市ガス供給系以外にＰＶ由来の水素を添加した際の熱電－総合効率の変化を調べ、需要予測から高いｴﾈﾙｷﾞｰ自立度の達成を明らかにしている。さらに、都市部と居住区において、ﾏｲｸﾛｸﾞﾘｯﾄﾞ内部でのＰＶからの水素製造、ｺｼﾞｪﾈ最適運用による水素消費をもとにｴﾈﾙｷﾞｰ自立度の最大化条件を最適化モデル解析から定量的に明らかにした。また、このＰＶ由来の水素－燃料電池の複合型ｼｽﾃﾑの実現可能性に関して、水電解装置の効率、副生水素の利用、水素の貯蔵と輸送問題を検討して、具体的に国内の離島へ適用した場合の経済有用性解析も行っている。

以上のように、本論文では、ﾊｰﾄﾞﾊﾟｽｴﾈﾙｷﾞｰを最小化すべく再生可能ｴﾈﾙｷﾞｰとｺｼﾞｪﾈの連携ｼｽﾃﾑの最適条件を詳細に解析し、ﾏｲｸﾛｸﾞﾘｯﾄﾞ系におけるｴﾈﾙｷﾞｰ自立性を定量的に評価・検証している。

よって、本論文は、博士（工学）（同志社大学）の学位論文として十分な価値を有するものと認められる。

総合試験結果の要旨

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要　　旨：

本論文提出者は、2013 年 9 月に同志社大学大学院工学研究科博士課程（前期課程）を修了後、2013 年 9 月より本学大学院理工学研究科博士課程（後期課程）に在学している。提出者は、博士課程（前期課程）から博士課程（後期課程）の在学中にわたり一貫して、太陽光発電と燃料電池の連携ｴﾈﾙｷﾞｰｼｽﾃﾑの解析的研究を行ってきた。

本論文の主たる内容は、International Journal of Hydrogen Energy に 1 編、日本機械学会論文集に 2 編、Global Resource Management に 3 編にすでに公表されており、国際学会においても 3 件の講演を行い、内外の学会において十分な評価を得ている。

2016 年 7 月 28 日（木）午前 10 時より約 2 時間にわたり、提出論文に関する学術講演会（博士論文公聴会）が開かれ、種々の質疑応答が行われたが、提出者の説明により十分な理解が得られた。さらに講演会終了後、審査委員により学位論文に関連した口頭試問を実施した結果、十分な学力を確認できた。なお、提出者は英語による論文発表を行い、語学試験にも合格しており、十分な語学能力を有すると認められる。

よって、総合試験の結果は合格であると認める。

博 士 学 位 論 文 要 旨

論 文 題 目： Conceptual study on the energy independence of fuel cell cogeneration systems using solar energy
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氏　　名： Lamas De Anda Jorge Eduardo

要　　旨：

The combustion of fossil fuels in large centralized power plants for energy supply has become increasingly discouraged due to concerns regarding pollution, resource availability and efficiency, among others. Introduction of renewable energies continues to be a difficult issue to this day. Wind and solar energy have had the most growth in recent years. However, one of the major concerns with them is the instability in power output, and thus most energy systems designed to use renewable energies consider utilizing the main power grid to stabilize the output. But in order for renewable energies to make a visible impact, the penetration of such systems needs to increase to town and city scales, which is expected to cause difficult challenges if all systems depend on the grid. Therefore, there is a need to design and develop distributed energy supply systems with high grid independence. In this thesis, residential and town-scale distributed energy systems with high grid independence are introduced with the intention to address two major issues: systems with access to an existing energy infrastructure where the contribution of the grid is minimized, and systems without access to an existing energy infrastructure where primary energy consumption is minimized.

This thesis begins with a detailed description of the current energy infrastructure and the efforts up to now to develop distributed energy systems using renewable energies with high independence. It is found that most approaches in literature, where access to the grid is possible, rely heavily on it and offer no insight on how grid dependence will affect the grid's performance or in the future. Systems that are fully independent from the power grid are found to have a delicate balance between energy demands and storage and many studies consider the inability of the system to meet demands. In order to create reliable systems with minimum grid dependence, the different available distributed energy resources (DER) are summarized.

Fuel cells are believed to offer the best alternative to distributed power generation because they rely not on fossil fuels directly, but on hydrogen that can be generated from several resources. A residential energy supply system using fuel cell cogeneration and solar photovoltaics and hydrogen storage is proposed. Exhaust gases from fuel cells have high temperature which can be used to generate hot water for residential use. Commercial fuel cells for residential use are fueled with methane from city gas. Methane is transformed into hydrogen using part of the fuel cell's exhaust heat. The effects of partially substituting methane for hydrogen generated from surplus energy on the heat output of the system are presented in this thesis. Considering these effects, the performance of the

residential cogeneration is studied and compared against solar PV systems that consider grid connection. The proposed system is found to achieve 97% grid independence, compared to PV and battery systems which reach only 64% grid independence. However, the economic feasibility is low because grid electricity currently has a very low cost, which favors the systems with high grid dependence. Therefore, an approach to larger scale systems without access to the main power grid is undertaken next.

The thesis presents a hydrogen micro-grid structure using fuel cells and solar energy for interconnection between residential and commercial/public sectors with complete grid independence. This structure presents a problem of mathematical optimization because the capacity of the DER components needs to be balanced with the size and energy demands of the micro-grid. Mathematical optimization is summarized and the appropriate optimization method is selected and justified. Using this method, the optimization model for the proposed micro-grid is developed and simulated. The objective of the model is to minimize external hydrogen consumption while meeting completely all energy demands. Solar irradiation and energy demands from different areas in Japan are considered and different simulation scenarios corresponding to different energy demands are used for simulation.

After adjustments in the model to improve computation time and feasibility, the objective function of the model is defined as the maximum fuel savings that can be achieved for a grid of similar size using the conventional energy supply system. It is found that fuel savings ratio does not follow an obvious trend with respect to the number of residences included in the grid. Instead, the model is able to find the optimum balance between energy demand and supply between the commercial/public facility and the number of residences. If the size of the facility is varied, a visible trend is observed on the number of residences that depends on the facility type (*i. e.*, the energy demand patterns). The capacity of the fuel cells used also shows a visible trend depending on the size of the facility. These trends can be better understood by analyzing the model's output results that correspond to hourly operation schedule for each component of the micro-grid. Fuel savings ratio for the studied scenarios was high in all cases, ranging from 26% to 36% compared to the currently installed energy supply system. The major impact on the model's ability to provide feasible solutions was found on the variable bounds used for the variables regarding fuel cell capacities and number of residences. No visible trend was observed between the variable bounds and the value of the solutions found, and no current methodology for choosing the appropriate bounds has been identified. This is regarded as the model's largest weakness; however, the solutions found do represent feasible solutions with higher fuel savings than the current system even if they are not the global maximum.

In order to illustrate the actual benefits of using hydrogen instead of fossil fuels for power generation, the capability for generating hydrogen through different channels is described, focusing mainly on reformation of hydrocarbons and water electrolysis. The actual situation and the feasibility of these hydrogen generation methods are explained and their consideration for use in power generation using micro-grids is justified.
Since it was found that residential cogeneration systems were not economically competitive against fully developed power grids like those in Japan, the economic feasibility of the independent hydrogen micro-grid is analyzed for an isolated area where access to the main power grid does not exist and the energy costs in the currently installed power generation system are relatively high. The isolated area selected is a medium sized Japanese island

to the south, where renewable energies have not yet reached a significant share of the total energy mix. Energy demands and solar irradiation of the area are used to run simulations with the optimization model, for different facility size and types. Variable bounds used in these simulations were common to the facility type in many cases, and computation time was around one minute when using data representative of one day per month. The model found high fuel savings for all cases, including their respective operating schedules for each component of the micro-grid. Higher fuel savings were generally observed for facilities with higher energy demands. The optimized number of residences for each facility type was found to be close to the existing ratio of households to businesses in the area, although this may not be always the case when applied to other study cases.

The economic feasibility of the proposed hydrogen micro-grid in Japanese islands is evaluated with respect to the current energy supply system. First, seven scenarios that combine the different sources of hydrogen fuel at different ratios are considered, including the shipping costs for fuel in cases where hydrogen cannot be produced at the island. Technology costs are obtained from the literature and the energy cost per kilowatt is analyzed during a twenty year period, corresponding to the micro-grid component with the longest lifetime. Economic feasibility was defined using only energy costs and payback time. All cases, except for small office type facilities, were found to be economically feasible for the studied case. The lowest cost of energy was found when on-site biomass and off-site industrial waste gases were used in equal ratios as the source of hydrogen. Other hydrogen source scenarios showed almost no change in the final cost of energy. It was also found that higher fuel savings were not directly related to lower energy costs for hotel and store type facilities, only for office type facilities. Maximizing fuel savings does, however, decrease greatly the need for large hydrogen storage tanks which represent a high portion of the initial investment. Also, higher fuel savings are considered to be important because the hydrogen generation methods, with the exception of reformation of natural gas, have a limited capacity for supplying a larger number of these hydrogen micro-grids.