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論 文
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Fuel Cell as an Alternative Distributed Generation Source under Deregulated Power Systems

李 光 延* · 金 世 鎬** · 金 一 煥** · 金 豪 贊†
(Kwang Y. Lee · Se-Ho Kim · Eel-Hwan Kim · Ho-Chan Kim)

Abstract - Because of the trend of deregulation, power industry is going through an unprecedented transformation in North America and Europe, and there are a host of acquisitions and mergers by the private sector to position themselves to take advantage of new business opportunities. Deregulation has accelerated the development of smaller generators and fuel cells will gradually become more attractive to mainstream electricity users as they improve in capability and decrease in cost. Fuel Cell technology is surveyed and the potential of using fuel cell as a distributed generation source is presented. This paper recommends the fuel cell power plants as alternative energy sources for distributed generation in Jeju Island, Korea. This will help in increasing fuel efficiency, at least double the current thermal plants', increasing the reliability of power supply, reducing the dependency on the HVDC link, providing quality power to the growing infrastructure, and maintaining clean air in meeting the free-trade international island.

Key Words : Deregulation, Distributed Generation, Fuel Cells

1. INTRODUCTION

Small scale power generating technologies, such as gas turbines, small hydro turbines, photovoltaics, wind turbines and fuel cells, are gradually replacing conventional generating technologies in various applications in the electric power systems. These distributed technologies have many benefits, such as high fuel efficiency, short construction lead time, modular installation, and low capital expense, which all contribute to their growing popularity. The prospect of independent ownership for distributed and other new generators, as encouraged by the current deregulation of the generation sector, further broadens their appeal. In addition, the industry restructuring process is moving the power sector in general away from the traditional vertical integration and cost-based regulation and toward increased exposure to market forces. Competitive structures for generation and alternative regulatory structures for transmission and distribution are emerging from this restructuring process [1].

† 교신저자, 正會員 : 濟州大學校 電氣電子學部 敎授
E-mail : hckim@cheju.ac.kr
* 正 會 員 : 펜실베니아주립대 전기공학과 교수
** 正 會 員 : 濟州大學校 電氣電子學部 敎授
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Electricity competition has led to significant changes in the operation of the bulk power grid, which are the power plants and high-voltage transmission facilities that make up the wholesale power market. More electricity is being shipped longer distances over a transmission system that was initially designed only to provide limited power and reserve sharing among neighboring utilities. Electric utilities that were once solely responsible for ensuring that adequate generation was available to meet demand now purchase a substantial amount of the power they need from the wholesale market, relying on independent power producers to build and operate plants.

Most new electricity generation is being built not by regulated utilities, but by independent power producers. These companies assume the financial risk of investment in new generation, and their success rides on their ability to generate electricity at a low cost.

These dramatic changes affecting the industry led to important structural changes. Independent power producers, which were once infant industries, now dwarf many utilities. Utility merges, which were once rare, are now commonplace. While utilities had service areas that were limited to a single state or region, independent power producers are international companies that can build power plants across the globe. Many utilities that were once vertically integrated divested themselves of generation, either voluntarily or because of the state law.

2. DISTRIBUTED GENERATION

The concept of DG has a variety of meanings, often resulting in some confusion. DG will refer to any modular generation located at or near the load center. These small, self-contained, decentralized power systems are categorized as photovoltaic, mini-hydro, and wind systems or in the form of fuel-based systems, such as fuel cells and microturbines [2].

A shift in the economies of scale recently took place where smaller power plants with a few dozens of MW's, instead of few GW's, became more economical. Also, generators with renewable sources as wind or solar energy became more economically and technically feasible. This has resulted in the installation of small power plants connected to the distribution side of the network, close to the customers and hence referred to as "embedded" or "distributed" generation.

Recently, power market liberalization in Europe and North America has resulted in an increase in the number of smaller power producers participating in the electricity market giving rise to a renewed interest for DG. This led to a considerable increase in the proportion of DG in the network. A study by the Electric Power Research Institute (EPRI) indicates that by 2010, 25% of the new generation will be distributed [6].

The introduction of DG to the distribution system will have a significant impact on the flow of power and voltage conditions at the customers and utility equipment. These impacts might be positive or negative depending on the distribution system operating characteristics and the DG characteristics. Positive impacts include:

1. Voltage support and improved power quality.
2. Diversification of power sources.
3. Reduction in transmission and distribution losses.
4. Transmission and distribution capacity release.
5. Improved reliability.

However, some operating conflicts related to over-current protection, voltage regulation, power quality problems, ferroresonance and others might result when the distributed generators are to operate in parallel with the utility distribution system.

The International Energy Agency (IEA) identifies 5 major factors that contribute to the renewed interest in DG [3]:

1. Electricity market liberalization.
2. Developments in DG technology.
3. Constraints on the construction of new transmission lines.
4. Increased customer demand for highly reliable electricity.
5. Environmental concerns.

2.1. DG technologies

There are various types of distributed generation technologies ranging from the well established reciprocating engines and gas turbines to more recent types of renewable sources such as wind farms and photovoltaic. Emerging technologies such as fuel cells and micro-turbines are recently commercialized. DG technologies can generally fall under two main categories:

Combined heat and power (CHP): CHP plants or cogeneration are power plants where either electricity is the primary product and heat is used as a byproduct, or where heat is the primary product and electricity is generated as a byproduct. The overall energy efficiency is then increased. Many DG technologies, such as Reciprocating engines, Micro-turbines and Fuel cells can be used as CHP plants.

Renewable energy generation: This refers to distributed generation that uses renewable energy resources such as the heat and light from the sun, the wind, falling water, ocean energy and geothermal heat. The main DG technologies falling under this category are wind turbines, small and micro hydro power, photovoltaic arrays, solar thermal power, and geothermal power [3].

By relying on dispersed small-scale generators, combined with other distributed resources such as flywheel storage devices and sophisticated control equipment, utilities can avoid costly investments in large, often the polluting central plants. They can also deploy generating assets more flexibly as needed, and at the same time reduce transmission and distribution losses.

2.2 Types of distributed resources

In principle, any of the alternative or renewable energy sources, from biomass to photovoltaics, is suitable for inclusion in the kind of "microgrid" as devising for the "virtual utility" of the future.

Even with a modest sustained rise in natural gas prices, technologies only recently seen as merely near-competitive could suddenly become much more attractive. And utility plans allowing customers to opt for "green power" are helping promote great reliance on renewables.

But wind and biomass are constrained by the availability of wind and land, and photovoltaics will become cost-competitive only if gas prices double. Partly for those reasons, the two candidate technologies for distributed generation that are arousing the most excitement right now are fuel cells and microturbines. Companies touting novel approaches to the design of fuel cells and microturbines have been experiencing the kind of Wall Street roller-coaster rides ordinarily reserved for dot.coms. And in those stories there are good grounds for excitement, but also some cautionary tales [4].

Microturbines spinning into webs: As for miniature gas-fired turbines, they are arousing just as much excitement. More or less arbitrarily defined as micro (30-200 kW and above), mini (500-1000 kW), and small (up to 15 MW), such turbines are generally expected to be reliable (even though their rotation rates are high), quite efficient (albeit less so than large combined-cycle plants), and readily produced and deployed (despite the concerns about grid interoperability). Microturbines and fuel cells can be deployed not only in isolation but also in combination. Marrying the two technologies could have prodigious advantages. Among the gains are overall system efficiency and recovery of pollutants, including greenhouse gases [4].

Will turtles win the race?: While there is no shortage of announcements of "breakthrough" about to "revolutionize" the way energy is converted and distributed, when attempts are made to follow up on some of them, calls sometimes go unanswered. Many of these revolutionary technologies seem not ready for prime time. In the end the impression is that the more substantial developments in distributed generation are evolutionary, and come largely from firms already well-established in their fields of endeavor [4].

Some solid milestones: One especially promising feature of distribution generation is its ability to supply the power-hungry electronics installations that account for a substantial share of demand growth. The idea that their proponents claim will be able to generate electricity more cheaply and efficiently than gas-fired plant, is for all usable fuels to be converted and for carbon emissions to be fully sequestered, so that the technology essentially emits no carbon.

2.3 Limited impact on fuel conservation

Just about any smaller-scale energy source has the potential to help reduce reliance on natural gas: by providing peaking power where needed, cutting losses and costs associated with distribution and transmission, and providing a backup to centrally generated electricity. Distributed generation and storage also can yield greater trustworthiness than the "three nines" (99.9 percent reliability) that has been the power industry standard.

A major limitation of the distributed-generation concept, however, is that the most promising technologies - both fuel cells and microturbines - almost always rely on natural gas as the preferred feedstock. Thus they can do little to cut back on the use of gas beyond improving distribution efficiencies - by reducing line losses, for example, and allowing for energy to be used more flexibly [4].

In Europe (where the weather conditions are really variables and the forecast are available for limited period ahead of time), the Photovoltaic (PV) system needs to be over-dimensioned and integrated with batteries and Diesel Generator Set (DGS) for back-up purpose. Because of these limits the PV has been rarely chosen as energy supply in the off-grid industrial application which requires more than few kWh/day. The wind Generator (WG), despite of its reduced cost comparing to the PV solution, is not so diffused in Europe because of the weather conditions.

The European weather conditions do not allow designing PV only and/or WG only stand alone plants, despite of these technologies are available for energy supplying in the off-grid system. The High Integrated Hybrid System (HIHS) instead permits to design a power supply system able to guarantee the continuity of the supply mixing the different renewable energy sources - like PV, WG (even micro-hydro if possible) - limiting the DGS use for back-up purpose only. A way to increase sustainability of the system consists in substituting the DGS backup set with a fuel cell (FC). In this way, it is possible to use the energy surplus to produce, by a hydrolysis process, the hydrogen needed from the FC. In the case of FC, the costs are higher because of the absence of a real market for FC maintenance. FC cost will be reduced in the next years because of the increase of the FC production. In particular, the possibility of substituting the Diesel Generator backup group with a fuel cell for supplying isolated telecommunication devices is investigated both through the energy balance and an economic investment. Using the fuel cell technology as backup device the need of periodic maintenance and refueling operation is limited or removed. Accounting environmental cost, the photovoltaic-wind-fuel cell configuration, having this latter near-zero emission, permits an increasing of environmental sustainability and then a decreasing of the increment due to external costs in the electric power generation [5].

3. FUEL CELLS

A fuel cell is similar to a battery in that an electro-chemical reaction is used to create electric current. The charge carriers can be released through an external circuit via wire connections to anode and cathode plates of the battery or the fuel cell. The major difference between fuel cells and batteries is that batteries carry a limited supply of fuel internally as an electrolytic solution and solid materials (such as the lead acid battery that contains sulfuric acid and lead plates) or as solid dry reactants such as zinc carbon powders found in a flashlight battery. Fuel cells have similar reactions; however, the reactants are gases (hydrogen and oxygen) that are combined in a catalytic process. Since the gas reactants can be fed into the fuel cell and constantly replenished, the unit will never run down like a battery.

Fuel cells generate electricity through an electrochemical process in which the energy stored in a fuel is converted into DC (direct current) electricity. The process is similar to that of a battery. Because fuel cells generate electric energy without combusting fuel, they have many advantages. Some are as follows:

- High energy conversion efficiency
- Modular design
- Very low emissions
- Low noise
- Fuel flexibility
- Cogeneration capability
- Rapid load response

All fuel cells have the same operating principle: an input fuel is chemically transformed in the fuel cell to create an electric current. Fuel cells consist of an electrolyte material, which is sandwiched in between two thin electrodes, in this case, a cathode and an anode. The oxygen (i.e., air) passes over the cathode and the input fuel passes over the anode where it catalytically splits into ions and electrons [6].

3.1 Types of fuel cells

There are four main types of fuel cells currently being developed and/or distributed. They include Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC), and Proton Exchange Membrane Fuel Cells (PEMFC). Technological comparisons between these four fuel cells are outlined in Table 1. Zinc Air, Alkaline Fuel Cells, and Regenerative Fuel Cells are other technologies that are similar in design or output to fuel cells.

Specific applications: Fuel cells allow for a number of different types of applications, including stationary power sources, portable power sources, micro power sources, and those found in vehicles. Among the fuel cells, the high temperature fuel cells, MCFC and SOFC, are primary candidates for large power production for stationary sources.

Stationary power sources: Stationary power sources are connected to the utility grid. However, these types of fuel cells have the capability of providing premium power quality that the utility grid and momentaries cannot, especially in the cases of voltage sags. Premium power can be cleaner, less polluting, more secure, and more reliable. For these reasons, hospitals, plastic extruders, data centers, telecommunication switching centers, and cell phone towers will find fuel cell technology valuable.

Fuel cells may be used in residential homes, small commercial businesses, and larger commercial or industrial companies for emergency backup electricity, baseload / lifeline electricity, high-power quality requirements (i.e., in-home office connections), energy self-sufficiency, and remote off-grid locations. Utilities and other energy providers may also use fuel cells to ensure high customer power quality, meet transmission upgrade deferrals, and fit in with the "Green Power" market. Such distributed generation is modular, provides ease of sitting, and ensures lower capital cost.

Table 1 Technology comparison [6]

	PAFC	MCFC	SOFC	PEMFC
Electrolyte	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer
Operating Temperature	375°F (190°C)	1200° F (650°C)	1830°F (1000°C)	175°F (80°C)
Fuels	Hydrogen (H2) Reformate	H2/CO/ Reformate	H2/CO2 /CH4 Reformate	H2 Reformate
Reforming	External	External Internal	External Internal	External
Oxidant	O2/Air	CO2/O2/Air	O2/Air	O2/Air
Efficiency (HHV)	40-50%	50-60%	40-80%	40-50%

Portable power sources: Portable power sources are not connected to the utility grid. These fuel cells allow consumers the opportunity for portable power for emergency equipment, hand-held power tools, and road signs.

Micro power sources: Like portable power sources, micro power sources are not connected to the utility grid either. These types of fuel cells have the capability of being manufactured in sizes that will comply with the smallest power requirements. Hand-held computers (i.e., 3 Whr), notebook computers (i.e., 40 Whr), and cellular telephones (i.e., 3 Whr) are a few such examples. With approximately 400 million cell phones shipped to consumers in the year 2000, such technological devices promise to gain consumer attention as the world moves toward fuel cell use. The market for portable devices translates to an energy requirement of approximately 2.5 million kilowatts.

Vehicles: Fuel cells are currently being tested and marketed by many of the major automobile manufacturers. They provide an alternative to internal combustion engines, and because of their efficiency, will help reduce dependence on imported oil. Fuel cells also offer reduced vehicle emissions.

3.2 Molten Carbonate Fuel Cell (MCFC)

The Direct Carbonate Fuel Cell (DFC) is a type of molten carbonate fuel cell (MCFC) that internally reforms methane-containing fuels within the anode compartment of the fuel cell. This technology, as a mature product, has a projected net fuel-to-electricity efficiency of 55-60% and a total thermal efficiency approaching 85%. Sixteen fuel cell stacks were used in the SCDP with each stack rated at 125-kW and consisting of 258 cells. The cells and stacks were based on "direct fuel-cell technology" developed by Fuel Cell Energy (FCE). Natural gas is internally reformed into hydrogen, partially in an internal reforming unit and partially at the cells. The approach, Fig. 1, is a combination of indirect internal reforming (IIR) and direct internal reforming (DIR), which provides for better thermal management.

An MCFC stack dynamic model was developed to analyze a spectrum of dynamic responses from slow to fast transients [7]. Several assumptions were made in this work: a single stack temperature, representation of mass inventory, water-gas shift reaction at equilibrium, and inclusion of appropriate kinetics for the reforming reaction. These latter assumptions relate directly to the fast dynamics of the fuel cell stack. In [8] the model is extended by first deriving an explicit differential equation set and then representing polarization losses and temperature-dependent terms in the cell voltage. This is done by combining the basic lumped-parameter dynamic model with results from a three-dimensional cell performance model, correlated with experimental data.

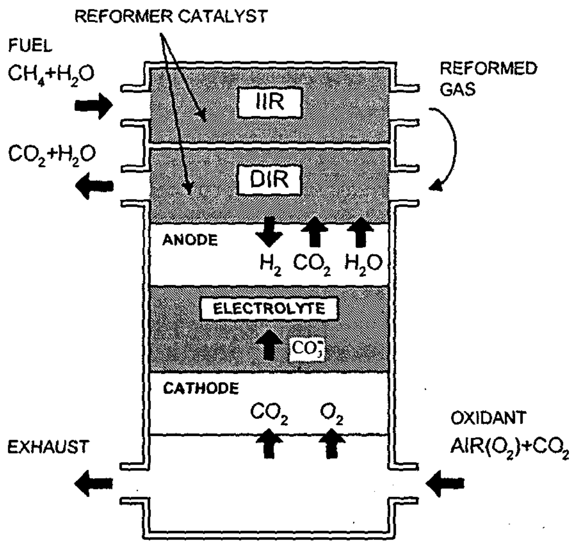

Fig. 1 IIR/DIR structure of MCFC stack

A simplified process flow diagram (PFD) of the Santa Clara Demonstration Project is shown in Fig. 2. This consists of a lumped representation of all sixteen stacks together with the balance-of-plant (B.O.P.). A dynamic model for the SCDP including B.O.P. has been described in [9]. The principle components in the PFD are:

- Cathode gas preparation including anode exhaust oxidizer and booster blower -
- Fuel processing including fuel preconverter and hydrodesulfurizer

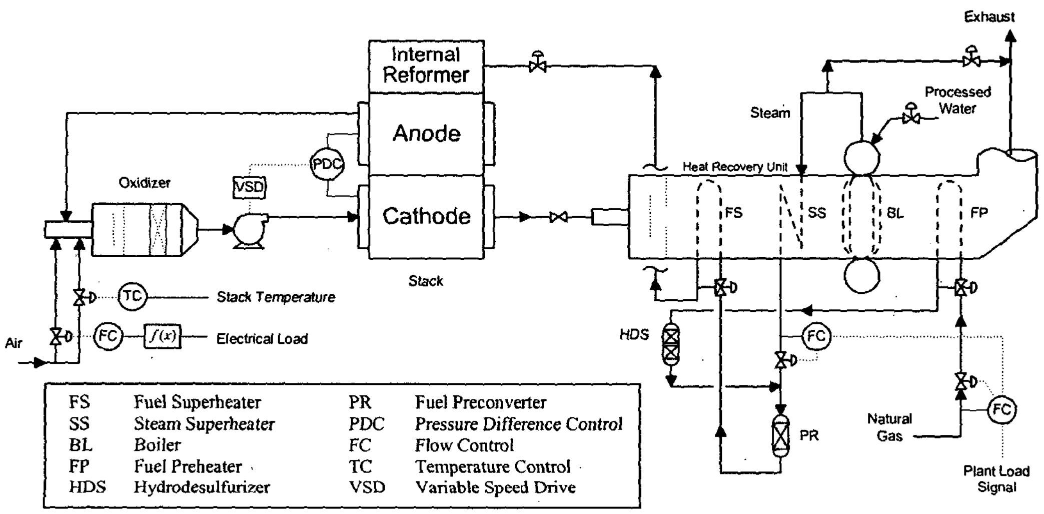

Fig. 2 Simplified process flow diagram for the Santa Clara Demonstration Project

- Heat recovery including steam generation and fuel and steam preheating
- Direct reforming (lumped) fuel cell stack

3.3 Hybrid power plant

The direct carbonate fuel cell (DFC) is a variant of MCFC in that it internally reforms methane-containing fuels within the anode compartment of the fuel cell. The integration of Direct Carbonate Fuel Cell with a gas turbine (DFC/T) is an emerging technology. The impetus for the integration is achieving ultra high efficiencies especially in large-scale power markets where the traditional combined cycles are approaching the sixty percent efficiency mark. The DFC/T cycle incorporates innovative design concepts for generation of clean electric power with very high efficiencies. One of the key features of the DFC/T combined cycle is the independency of the gas turbine pressure and the fuel cell pressure, which overcomes many of the operational issues during system transients [10].

Integration of a high temperature fuel cell with a gas turbine has recently been the focus of development by various organizations. The DFC/T hybrid system concept is based on integration of an atmospheric pressure internally reforming Direct Fuel Cell with a gas turbine. The power plant design utilizes a heat recovery approach for extraction of heat from the balance-of-plant. The fuel cell plays the key role by producing the larger share of the power. The gas turbine is utilized for generation of additional power by recovering the fuel cell byproduct heat, as well as for providing the air for the fuel cell operation. The DFC/T system concept is schematically shown in Fig. 3. Thefeed water humidifies natural gas in a waste heat recovery unit (HRU). The mixed fuel and steam are then preheated to about 550°C prior to entering the fuel cell anode.

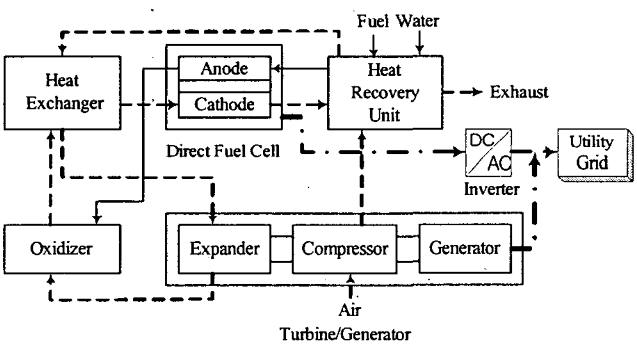

Fig. 3 Fuel cell/turbine hybrid system

The methane in the natural gas is reformed in the fuel cell and its chemical potential is converted to electrical energy. The anode exhaust, containing some unreacted fuel, is mixed with air and then oxidized completely in a catalytic oxidizer. In the turbine cycle, air is compressed to the operating pressure of the gas turbine and heated in a recuperator using waste heat from the fuel cell. The compressed air is then heated further to the operating temperature of the gas turbine expander by a heat exchanger (HE) located between the oxidizer and fuel cell cathode [11]. The hot compressed air is then expanded in the turbine providing additional electricity. The expanded air flows into the oxidizer, into the HE, and subsequently into the fuel cell cathode. At the cathode, the oxygen in the air and the CO2 from the anode are reacted to complete the electrochemical fuel cell reaction. The cathode exhaust provides the heat for preheating the air and fuel, and for generation of steam in the HRU before exiting the power plant. The intelligent control concept will be extended to the hybrid power plant that includes gas turbine.

4. IMPLEMENTATION OF FUEL CELL PLANTS IN JEJU ISLAND

Although small, Jeju Island power system in Fig. 4 has all power system components, including generation, transmission, distribution and retail services. It shows annual load increase of 8-9%, which is faster than that for the main land Korea. As the island thrives to become a free-trade international city, the need for reliable supply of electric energy sources is becoming urgent. Not only the supply of energy, but also the quality of power is becoming an important issue to meet the expectation of international standard in building the infrastructures. Therefore, expansion of generation facilities is an essential requirement for securing power system stability and reliability in Jeju Island. Furthermore, since the island is located in a hurricane path and is known to have frequent lightening, there has been frequent contingencies because of the system heavily depending on overhead transmission and HVDC tie lines.

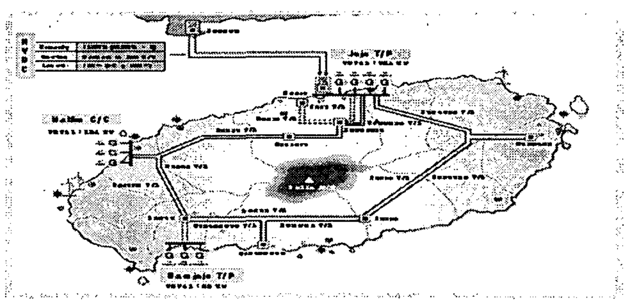

Fig. 4 Diagram of Jeju power system

The total installed capacity of Jeju Island is 587 MW, which includes 150 MW transfer through the HVDC from the mainland. The power transfer through the HVDC is about 50% of the total demand in the island, and more than 40% in the average annually. Recently, relatively larger units are being planned and thus, the impact of failure of a unit is expected to be greater than before. Most of the units use expensive oil as the fuel. wind turbine and LFG are new energy sources being introduced in recent years, 10 MW and 1

4.1 Large fuel cell plants

To reduce the dependency on the HVDC cable, large fuel cell plants are proposed in various locations. Fuel cell plants require the basic fuel in the form of LNG or bunker-C oil. In principle, all current oil-based thermal plants can be replaced or augmented by fuel cell plants in order to increase the fuel efficiency. Assuming the scenario that an LNG port will be available in South Jeju, the following plants are possible sites in the southern Jeju Island:

- Two 40 MW Fuel Cell Plants in South Jeju near the LNG port.
- One 40 MW Fuel Cell Plants in Joongmoon/Seoquipo
- One 40 MW Fuel Cell Plants in Hanra S/S
- One 40 MW Fuel Cell Plants in Hanrim S/S

In addition to the sites in the southern Jeju Island, fuel cell plants can be located in the following sites in the northern Jeju Island:

- Two 40 MW Fuel Cell Plants in Jeju T/S
- One 40 MW Fuel Cell Plants in Shinjeju S/S
- One 40 MW Fuel Cell Plants in Dongjeju S/S

Some units can be in the hybrid with gas turbine in order to increase the fuel efficiency to over 80%.

4.2 Small fuel cell plants

In addition to the large fuel cell plants for maintaining capacity for the Jeju Power System, there are number of applications for localized use of fuel cell plants:

- Industrial
- Government facilities
- Universities
- Hospitals
- Apartment complex

Some units can be in the hybrid with combined heat and power production (CHP), such as ones used for industrial and apartment complex.

As long as there are fuel lines available, either for LNG or buncker-C oil, a unit of 250 kW can be installed on site next to the buildings.

5. CONCLUSION

The paper has proposed the fuel cell power plants as alternative energy sources for distributed generation in Jeju Island, Korea. This will help to increase the fuel efficiency, at least double the current thermal power plants', decrease environmental pollution, virtually to none, increase the reliability of power supply, reducing the dependency on the HVDC link, and provide quality power to the growing infrastructure in meeting the requirements for the free-trade international island. Substantial number of new plants can be planned with fuel cell technology and it's hybrid with gas turbine and/or combined heat and power production.

The bottleneck of the implementation of the fuel cell technology is the developmental cost. Although the initial investment cost is high, it's long term operation will reduce the total operation cost, in addition to the benefit of maintaining clean air for the Jeju island. As a means of reducing the capital cost, it is essential to develop the fuel cell technology as a national priority as in the United States and Japan. This will also reduce the maintenance cost for sustaining the fuel cell power plants as a viable alternative for long-term operation. Since its inception, the nature of producing electricity has favored large central-station generators, all interconnected in a vast web of transmission lines. Distribution lines carried this electricity to the homes, businesses and factories of the world. Years of technology research and development have produced smaller generators that can approach the low cost of grid-supplied electricity. In some cases, these smaller devices provide superior solutions to supplying electricity.

In recent years, deregulation has accelerated the development of these types of alternative technologies, as inventors see the opportunity to compete in market niches that did not exist a few short years ago. Fuel cells will start out as a high-cost technology, supplying electricity (and heat) to these niches and gradually become more attractive to mainstream electricity users as they improve in capability and decrease in cost. Fuel cells, used to generate electricity, are an up-and-coming solution to the energy problem, and may increase in popularity as the world moves toward the deregulation of the utility industry. Using new clean-energy options, such as hydrogen and fuel cells, will be an increasingly important part of the global energy mix in the coming decades. It is vital to our efforts to reduce greenhouse gas emissions over the long term. The potential benefits - economical and environmental - of a hydrogen economy are enormous.

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저 자 소 개

이 광 연 (李 光 延)

Kwang Y. Lee received his B.S. degree in Electrical Engineering from Seoul National University, Korea, in 1964, M.S. degree in Electrical Engineering from North Dakota State University, Fargo, in 1968, and Ph.D. degree in System Science from Michigan State University, East Lansing, in 1971. He has been with Michigan State, Oregon State, Univ. of Houston, and the Pennsylvania State University, where he is a Professor of Electrical Engineering and Director of Power Systems Control Laboratory. His interests include power system control, operation, planning, and intelligent system applications to power systems. Dr. Lee is a Fellow of IEEE, Associate Editor of IEEE Transactions on Neural Networks, and Editor of IEEE Transactions on Energy Conversion. He is also a registered Professional Engineer.

김 세 호 (金 世 鎬)

Se-Ho Kim received the Master and Ph.D. degrees in electrical engineering from Yonsei University, in 1985 and 1992, respectively. Currently, he is a professor with the faculty of electrical and electronic engineering, Cheju National University of South Korea. His current research interests include power system and renewable energy system operation.

김 일 환 (金 一 煥)

Eel-Hwan Kim received the B.S. degree from Chung-Ang University, Seoul, Korea, in 1985, and the M.S. and ph.D. degrees in Electrical Engineering from Chung-Ang University, Seoul, Korea, in 1987 and 1991, respectively. He is currently an professor in the Faculty of Electrical and Electronic Engineering at Cheju National University. His research activities are in the area of power electronics and control, which include the drive system, renewable energy control applications, and power quality.

김 호 찬 (金 豪 贊)

He received the B.S., M.S., and Ph. D. degrees in Control & Instrumentation Engineering from Seoul National University in 1987, 1989, and 1994, respectively. He was a research staff from 1994 and 1995 at the Korea Institute of Science and Technology (KIST). Since 1995, he has been with the Faculty of Electrical and Electronic Engineering at Cheju National University, where he is currently a professor. He was a visiting scholar at the Pennsylvania State University from 1999 to 2000. His research interests include robust adaptive control, wind control, and power control.