Distributed Fuel Cell Generation in Restructured Power Systems

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Abstract--**This paper emphasizes the role of fuel cells as one of the popular options for distributed generation (DG) applications in restructured power systems. Typical topologies of fuel cell-based distributed generation systems are introduced, and major issues concerning interconnection with the utility grid are highlighted. Also presented in the paper are some of the issues related to marketing and standardization of fuel cell DG technology. Finally, a few working examples of fuel cell-based DG systems in the US and around the world are reviewed and their operation and performance characteristics are discussed.**

Keywords—**Fuel cells, restructured power systems, DG applications**

I. Introduction

In view of the major changes taking place in the power system infrastructure, the trend is to actively engage distributed generation (DG) technology to meet the increasing demand for energy services and quality. DG technology involves the use of small generators, ranging between 2-50 MW, and situated at strategic points near load centers. The most popular distributed generators include microturbines, fuel cells, biomass, diesel, small wind, and photovoltaic (PV) generators [1].

However, one of the most feasible and attractive DG is the fuel cell technology. This is partly due to the fact that wind and biomass are constrained by the continuous availability of wind and land, and PV generation relies on the availability of solar power. Moreover, small generating plants, utilizing diesel generators, produce emission, which is harmful for the environment. In contrast, the fuel cell-based DG system produces almost zero emission and provides a high efficiency and modularity of its output. Also, when used in conjunction with a microturbine or a mini turbine, the fuel cell system can achieve higher efficiencies.

In addition, there are various other attractive applications of fuel cells, such as aerospace industry, automotive industry, and as portable power units, which give added encouragement to the exploration of their use as a DG power source. The above-mentioned applications of fuel cells are presented in the following section, which basically gives a clear idea, as to why it is being seriously considered as a major DG power source contender in today's restructured power system environment.

A. Commercially Popular Fuel Cell Applications

Recently, one of the major applications of fuel cells is in the automotive industry. When compared to internal combustion engine (ICE) efficiencies of about 10-30%, fuel cells have shown efficiencies ranging between 30-40% for automobile applications [2]. Another popular application of fuel cells is in the aerospace industry, wherein the alkaline fuel cell (AFC) is the popular choice. Primarily, *NASA* had developed this technology for its space missions.

Finally, fuel cell based portable power systems have recently attracted the attention of most domestic power consumers. Fuel cell based portable systems depict long life, low mass, high energy density, and low start-up time [2]. All of these successful applications have basically encouraged many independent power producers to adopt the fuel cell based DG technology as a serious option. Before moving on to the technical description of fuel cell DG systems, it is useful to understand the basic operation of the system, which is presented in the ensuing section.

B. Fuel Cell-Based Power Systems

A typical fuel cell-based power system is depicted in Fig. 1. Basically, the last stage of a fuel cell power system involves the use of power electronic converters. The converter could be a dc-dc or a dc-ac unit depending upon the load type [2]. Obviously, for a grid-connected mode of operation, the converter is a dc-ac inverter. The use of grid-connected fuel cells will necessitate the review of many challenging issues, which are considered later in this paper.

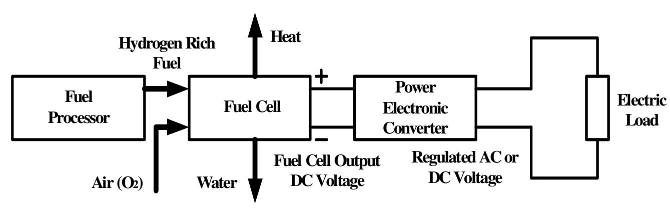

Fig. 1. Block diagram of a fuel cell-based power system

Typically, a fuel cell system with an output of approximately 200kW is only about 10 x 25 x 12 feet in size. Thus, the packaged nature of fuel cells defies the need for large sites, hence can be easily stationed in small area for operation [3]. Furthermore, theoretical efficiencies could reach values of greater than 60% and those for fuel cell hybrids reach even greater than 70%.

II. COMPARATIVE STUDY OF DG POWER SOURCES

Phosphoric Acid (PAFC) types of fuel cells are currently available in the 200 kW range. Also, Proton Exchange Membrane Fuel Cells (PEMFCs) are commercially successful for automotive applications since they are reasonably priced at about \$200/kW. This success has lured the utility companies to generate small amounts of power in the 100-200 kW range using PEMFCs.

Environmentally friendly renewable energy technologies such as PV and clean and efficient fossil fuels, and DG technologies such as microturbine generators and fuel cells are among the most promising generating systems. A comparative study on the emission levels of DG was carried out as depicted in Figs. 2(a) - 2(c).

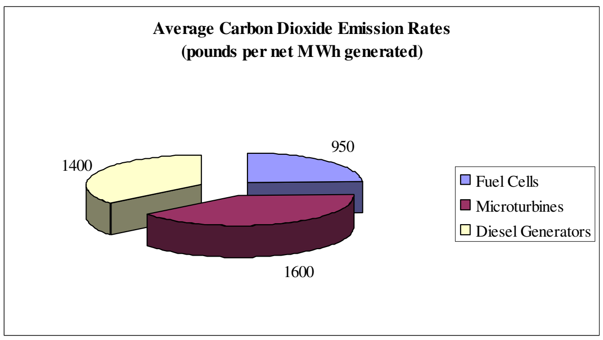

Fig. 2 (a). Comparative plot of average carbon dioxide emission rates

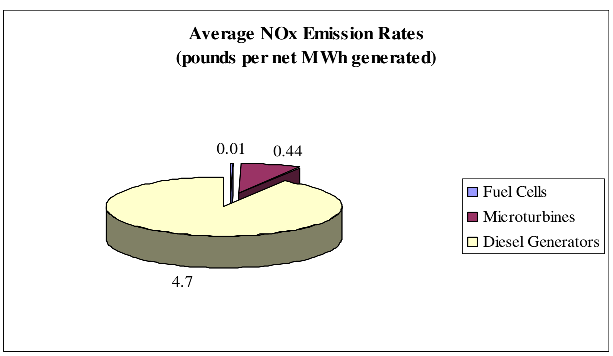

Fig. 2 (b). Comparative plot of average NO_x emission rates

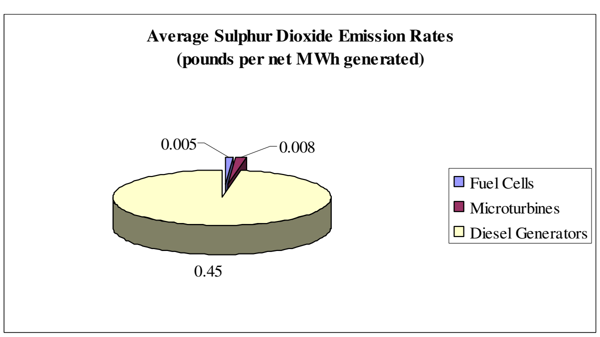

Fig. 2 (c). Comparative plot of average SO_x emission rates

In these figures, fuel cell DG systems generate smaller amounts of toxic emission, thus proving to be an environmentally friendly source of DG. It is apparent that CO_2 is the major emission of fuel cells. The reason for this stems from the fact that the hydrogen which is the primary fuel for fuel cells, is not readily available in nature, and needs to be produced using hydrocarbon fuels. These fuels are treated in a reformer, which leads to the generation of decent proportions of CO_2.

Fig. 3 depicts the power range for various DG systems. Here, fuel cell-based DG systems exhibit wider ranges of operation in the high power region. Thus, they can be selected for a wider range of applications, when the distributed power demand is between a few kW to few tens of MW. Furthermore, fuel cells can pair up with microturbines and internal combustion (IC) engines, for higher power applications.

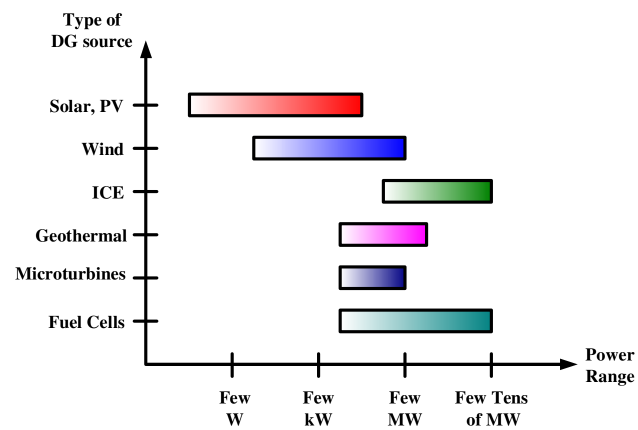

Fig. 3. Power ranges of DG technologies

Although hybrid DG systems are advantageous, they also have their share of drawbacks. One major problem is related to the fact, that microturbines and fuel cells have a slow response. In order to overcome such problems, the micro-grid concept was introduced which is basically a collection of small generating sources, storage systems, and loads, connected to the power grid as a single entity. Micro-grid interfaces with and can respond to grid control signals [4]. This interface isolates the two sides electrically, and at the same time, interconnects them economically.

III. TYPES OF FUEL CELLS FOR DG APPLICATIONS

The popular choices for DG are Phosphoric Acid FC, Molten Carbonate FC, Solid Oxide FC, and the Proton Exchange Membrane FC. Their applications in DG are briefly discussed below.

A. Phosphoric Acid Fuel Cells (PAFC)

Typically, PAFC units of the order of 250-300 kW are available for commercial cogeneration, and more than 150 of such units are in operation worldwide [5]. The typical efficiencies of such units are 40-50%, and the cost of production of power is approximately \$4200/kW, which is beyond the economic margin unless a financial benefit can be demonstrated from the PAFC's emissions, power quality, and reliability merits [5].

B. Molten Carbonate Fuel Cells (MCFC)

MCFC operates at higher temperatures of the order of 600°C and was initially marketed for 1-5 MW plant applications. This system has a much higher efficiency compared to PAFCs with values reaching as high as 50%. The MCFC-based systems are typically rated at around 200 MW and exhibit an efficiency of about 75%. Upon further research, the MCFC's cost of power production is estimated to be as low as \$1000/kW [5-7]. A hybrid MCFC/turbine cycle for maximizing the efficiency is shown in Fig. 4. In such a system, about 70% of the power is produced by fuel cell and about 15% comes from the gas turbine generator.

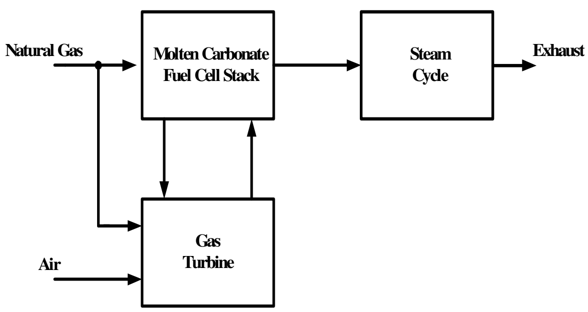

Fig. 4. A MCFC-hybrid power cycle

C. Solid Oxide Fuel Cells (SOFC)

Comparatively speaking, a 100 kW MCFC system uses about 100-110 cells in stacks, whereas, a similarly rated SOFC system would use about 1150 cells [5]. An example of a SOFC-based cogeneration plant is as shown in Fig. 5. Here, pressurized air and fuel are the inputs to the SOFC, since pressurized SOFC is being preferred for cogeneration purposes. The exhaust quality obtained by these units is comparatively higher. The hybrid fuel cell system, using a pressurized fuel cell, combined with the use of gas turbines, provides high efficiency and low emissions. A higher efficiency is gained by using the thermal exhaust from the fuel cell to power a non-combusting gas turbine.

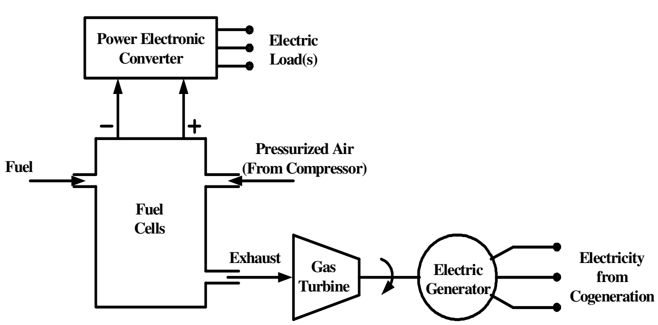

Fig. 5. Typical layout of a SOFC-based cogeneration plant

D. Proton Exchange Membrane Fuel Cell (PEMFC)

This technology has attracted the attention of most utility companies since it has produced extremely low cost power, compared to other fuel cells. The cost of power production in PEMFC-based automobiles is as low as \$100-\$150/kW, which provides a competitive potential for stationary power production. It is expected that a successful market for PEMFC will have a significant impact on power generation since it could shift the primary role of the present-day grid to back up and peaking power [5]. In addition, PEMFCs find applications in cogeneration, in providing premium power, and in households [5-8].

It is apparent that several fuel cell types have strong potentials for entering the DG market. They can basically provide cost-effective cogeneration, grid-support, and asset management. Also, long-term plans for fuel cell are underway with advanced designs for combined-cycle plants, which could eventually compete for a share of the DG market.

IV. FUEL CELL BASED HYBRID DG SYSTEMS

As stated earlier, microturbines are available ranging from 50-100 kW [9]. Individual fuel cell units ranging from 3-250 kW can be used in conjunction with microturbines for higher power DG applications. The other popular DG technology is the PV power generation system, which is suited to provide up to 250 kW of electricity. These topics are discussed further as follows.

A. Fuel Cell-Microturbine Hybrid DG System

Emission specifications for the pressurized SOFC design is less than 1.0 ppm NOx and almost zero level of SOx. Another unique advantage of this unit is that a small percentage (about 15%) of fuel is wasted. The exhaust thermal energy is used to drive the microturbine. The hot exhaust from the plant supplants the microturbine combustor during the normal steady operation. It must be noted here that microturbine forms no additional pollutants [10]. The SOFC type of fuel cell is chosen for this application since it operates at the highest known temperature among fuel cells, at about 1000°C, and can be operated at high pressure. All these features are added up to provide additional thermal and electrical efficiency for the hybrid unit.

A diagrammatic representation of such a unit is as shown previously, in Fig. 5. Typical rating of such a hybrid system is about 250 kW and efficiencies of greater than 60% are targeted for the future. An important point to be noted here is that the fuel cell supplies about 80% of the output power, whereas the microturbine supplies the remaining 20%. Hence, microturbine functions primarily as a turbocharger for SOFC, with additional shaft power coming from microturbine for electrical power generation [10].

The *National Critical Technologies (NCT)* panel has identified fuel cells and microturbines as 2 of 27 key technologies in US for maintaining the economic prosperity and national security [10]. Several utilities facing with the dilemma of increasing transmission capacity is opting for DG technology. Such efficient packages of about 250 kW size could avoid the need to increase transmission capacity for years to come [10].

B. Fuel Cell-Photovoltaic Hybrid DG System

Fuel cells are attractive options for intermittent sources of generation like PV, because of their high efficiency, fast response to loads, modularity, and fuel flexibility [11]. Such a system is able to smoothen the PV problem of intermittent power generation by utilizing the fast ramping capabilities of fuel cells. Unlike batteries, which get discharged after a short time of operation, fuel cells can continuously provide the required amounts of power as long as the reactants (fuel + air) are supplied. Thus, the quality of power fed to the utility system by the hybrid system is of improved nature. A simple schematic of a PV-fuel cell hybrid system is depicted in Fig. 6.

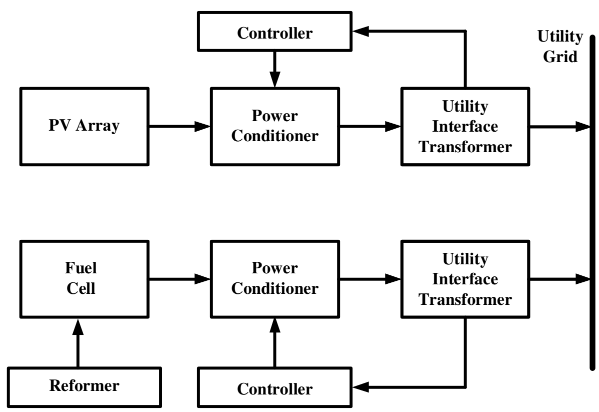

Fig. 6. Schematic block diagram of a fuel cell-PV hybrid system.

The Fig. 6 illustrates a grid-connected PV-fuel cell power plant including 2 feedback controllers, which basically can control the power conditioner switches. These power electronic switches, in turn, control the maximum power point and active and reactive power flows. In Fig. 6, the hybrid system consists of a PV array, a fuel cell stack, a reformer for purifying the hydrocarbon-based fuel, and power conditioners, which consist of dc-dc and dc-ac power electronic converters. The PV generator operates independently and is controlled to produce maximum available solar power. The fuel cell generating system is used as a supplement to this PV system to meet the system's power demand [11].

The PV array in Fig. 6 is made up of 80-100 series-connected, and 450-500 parallel-connected solar modules which produces 1.5-2 MW of power at 1400V. On the other hand, the fuel cell system made up of a PAFC unit, generates about 2 MW and satisfies the system's demand for active and reactive power. Such a combination of fuel cells with PV arrays proves to be feasible for solving the inherent problems of stand-alone PV systems. Furthermore, since conventional fossil fuel energy sources are diminishing at a fast rate, such energy sources are attracting even more attention from utility companies. Much research is being devoted to such hybrid systems to bring down their O&M costs and render them favorable over conventional gas turbines and diesel engines.

V. INTEGRATION OF FUEL CELL WITH UTILITY GRID

While designing fuel cell systems, it must be kept in mind that they are extremely small and weak systems. Hence, the utility interface issues, such as power quality, total harmonic distortion (THD), electromagnetic interference (EMI), and voltage sags/surges need to be considered. These issues apply to any new DG installations. Additional concerns include reactive power coordination, reliability and reserve margin, network back up, safety of operation, and accountability. In the following, some of the major issues are discussed briefly and their remedies are highlighted.

The fuel cell-based DG system operates in 2 modes, viz., the stand-alone mode and the grid-connected mode. While in the stand-alone mode, the fuel cell system is generally backed up by an energy storage source, in order to supply the load transients. On the other hand, in the grid-connected mode, the fuel cell system uses the back-up supply for start-up purposes. A typical layout of a fuel cell-based power system, interfaced with the utility, is shown in Fig. 7.

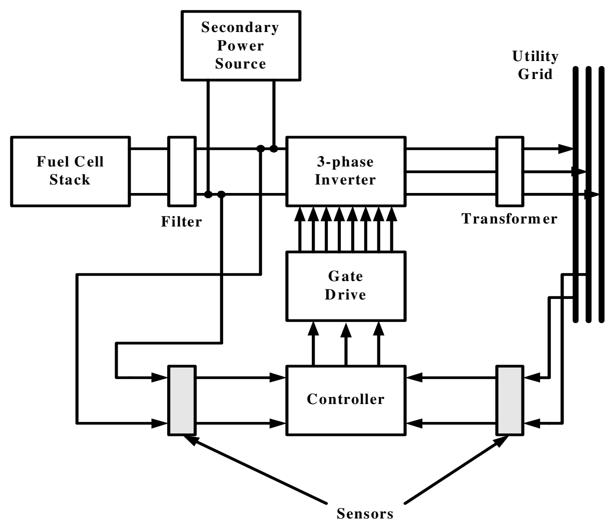

Fig. 7. Utility interface with a fuel cell system

The final stage of this system may utilize a transformer, which boosts the voltage to a suitable level for the grid interconnection. A multi-level dc/ac inverter may alternatively be used to increase the voltage to the level of the utility grid. These inverters have a unique structure, which allows them to produce high levels of voltage with low production of harmonics. By utilizing inverters, there is no need for the output stage transformer. An important application of power electronic converters for interfacing fuel cell systems with the utility system is that the converters can also provide ancillary services.

The grid-connected mode has a quick dynamic response and is capable of switching from a charged mode to a discharged mode, or any other state, in 20-30 ms. Hence, the grid-connected mode of operation is suitable for providing a number of ancillary services, such as voltage control and frequency compensation [12]. Accordingly, most DG systems would require energy management for coordinating resources and storage and providing control over the optimal energy usage and start-up. The power generating companies can use this technology to gain a competitive edge by appropriately shifting between generation and the use of electricity [13].

VI. MARKETING STRATEGIES AND STANDARDIZATION POLICIES

Since the advent of DG is taking place at a time when the electric power industry is undergoing a major restructuring phase, certain policies and regulations need to be followed by DG suppliers. Primarily, the aim of such policies are to create a competitive environment between a wide range of suppliers, thus, giving the customer a larger number of options to choose from. In this section, basic marketing strategies and standardization issues will be discussed, and their importance in the final analysis shall be summarized.

One of the major marketing strategies involves incentives that commend DG suppliers for commercializing the technology aggressively in the market. The aim here is to initiate a healthy competition among DG suppliers. At the same time, it is of prime importance that the incentives would not subsidize unused and overpriced DG equipment [14]. As is obvious, commercialization of a particular DG technology, fuel cells in this case, must comply with all aspects of electric power system restructuring policies.

An additional point to be discussed here when considering a breakthrough technology, such as fuel cell DG, is a set of standards that need to be followed for its successful operation. There have been critical ongoing studies in terms of the formulation of standards through the *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems* (IEEE Standard P1547). Some of the main goals of these studies are to provide manufacturers and end users with a well-defined set of operating and testing procedures to ensure a safe operation. In addition, standards are devised to provide the necessary details for technical procedures. The IEEE Standard P1547 facilitates the interconnection of one or more DG systems with the existing power system grid [15].

It is of utmost importance that the policies depict uniformity in their usage. Otherwise, the impact could directly affect the market penetration of the related DG technology.

VII. OPERATIONAL FUEL CELL–BASED DG SYSTEMS

It would be interesting to enhance the discussions carried out in this paper by reviewing how fuel cell-based DG systems actually work in practice. For this purpose, 2 examples of fuel cell-based DG systems shall be explained here. Firstly, a discussion is provided on the largest fuel cell project in the U.S. which is located in Anchorage, Alaska. Then a review is made on cogeneration plants for commercial buildings. The application discusses the supply of power to a nursing home in Pittsburgh, Pennsylvania.

A. Fuel Cell Plant in Anchorage, Alaska (1 MW Capacity)

This project is a typical example of a fuel cell-based DG system placed near a large retail customer. The fuel cell output provides power to a U.S. Postal Service International Sorting Center with its excess electrical output feeding the Chugach electricity distribution grid. The DG system is expected to provide 5-10% of the Chugach power market, i.e., 20-50 MW [16]. In 1997, Chugach installed 2 PAFC units on the military installation in Anchorage, which continue to provide the electric power support as of now. The peak load demand of the post office is 800 kW and each of the fuel cells is rated at 200 kW. There are 5 such fuel cell units in operation, which allows for 1 standby unit. The entire project is monitored and controlled by SCADA from the Chugach's electricity power control center [16].

B. Fuel Cell-Based Power System for a Nursing Home

In this case, the application, installation, and start-up of a 200 kW natural gas fuel cell system is used to power a healthcare facility. The fuel cell unit used for this purpose is 3m (width) x 7.3m (length) x 3.5m (height). The electrical design consideration has 2 main applications, viz., interconnection with the utility grid and the connection between the fuel cell units and the power electronic converters [17]. The unit is equipped to automatically isolate the grid-connected loads from the utility service in response to abnormal line conditions. In accordance with PURPA Act 210, the distribution utility developed a set of interconnection standards for grid-connected operation with cogeneration facilities [17]. It is worthwhile to mention that the set-up resulted in 2-2.50 cents/kWh saving. To date, the operation of this unit has been flawless and is expected to reach about 95% availability.

VIII. PROSPECTS FOR FUEL CELL DG TECHNOLOGY

The business plan of certain power utilities, which allow customers to opt for green power, is gaining a higher confidence of its customers and promoting a better service by reliance on renewables. Thus, nowadays, fuel cells and microturbines are the 2 main contenders for a hybrid operation and arousing the most excitement among utility planners [18]. As discussed earlier, fuel cell works in a stand-alone mode by drawing electricity from the grid when required, and feeds electricity back the excess capacity to the grid. Distribution loads such as homes and industries could be equipped with fuel cells and microturbines, which can send electricity back into the grid, and a flywheel device can store the excess power [18].

The miniature turbines are arousing just as much excitement. Broad classifications of these turbines are micro turbines (30-200 kW or higher), mini turbines (500-1000 kW or higher), and small turbines (up to 15 MW). These types of turbines are expected to be highly reliable, efficient, and readily deployed. The special challenges posed by such highspeed turbines, which rotate at speeds of 10,000 rpm, are solved by means of advanced power electronics. As stated before, a hybrid fuel cell and microturbine could pose major gains on overall efficiency and recovery of pollutants including greenhouse gases.

IX. CONCLUSIONS

In this paper, the basic operation of fuel cells and their applications as DG were presented. The paper pointed out some of the most up and coming fuel cell technologies. The hybrid fuel cell/microturbine and fuel cell/PV were explained with examples. These technologies are projected to create a positive impact on the reliability and economics of restructured power markets.

It is expected that several fuel cell technologies will enter the market for DG. These technologies can supply the needs for cost-effective cogeneration, grid-support, as well as asset management. Statements released from leading manufacturers and market research organizations reveal that the DG market is projected to be \$10 - \$30 billion by the year 2010. Much research is devoted at this point to lower O&M costs of hybrid DG systems to make them more favorable over conventional DG technologies. However, it is not certain when major fuel cell-based DG competitors will embark on massive marketing and utilization of large marketplaces for various fuel cell applications, even though the market for niche power applications seems quite open and the market may not be served quickly by existing power grids. The studies and analyses conducted in this paper, with regards to various DG technologies and more particularly fuel cells, provide a fundamental review of fuel cell basics for future development.

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XI. BIOGRAPHIES

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