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A Review article of Enhancement of Solid Oxide Fuel Cell Performance and Efficiency Using Power System Topology

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***Abstract*- The climate changes that are becoming visible today are a challenge for the global research community. The stationary applications sector is one of the most important energy consumers. Harnessing the potential of renewable energy worldwide is currently being considered to find alternatives for obtaining energy by using technologies that offer maximum efficiency and minimum pollution. In this context, new energy generation technologies are needed to both generate low carbon emissions, as well as identifying, planning and implementing the directions for harnessing the potential of renewable energy sources. Hydrogen fuel cell technology represents one of the alternative solutions for future clean energy systems. This article reviews the specific characteristics of hydrogen energy, which recommends it as a clean energy to power stationary applications. The aim of review was to provide an overview of the sustainability elements and the potential of using hydrogen as an alternative energy source for stationary applications, and for identifying the possibilities of increasing the share of hydrogen energy in stationary applications, respectively.**

***Keywords*-alternative energy, energy efficiency, fuel cell, hydrogen energy, stationary application.**

I.INTRODUCTION

Fuel cell technology can belong to either of the above categories. If the hydrogen fuel needed to power the fuel cell is generated from a renewable source, the fuel cell power generating unit is considered a renewable energy technology. i.e., wind and solar energy used to generate hydrogen to fuel a fuel cell stack. On the contrary, if hydrogen is produced from a fossil fuel source (e.g., natural gas or methane), the fuel cell is considered a nonrenewable energy technology. Through careful design, selected fossil fuel driven DGs can be built to oxidize some of the fossil fuel (by combining with oxygen) to produce heat. Such operation modes, whether in electromechanical (rotational) or electrochemical (fuel cell) systems, are referred to as combined heat and power (CHP) operation mode.

Most of the new DG technologies include power electronic devices to provide usable output power. These DGs are often referred to as power electronically interfaced DGs. Enormously improved power control of these generation sources has become possible by controlling their power electronic interfacing units. In a common approach the output voltage of these generation devices whether dc or ac is converted to a controlled output voltage. Fuel cells are being considered as a potential source of electricity among the various Distributed Generation technologies available. Fuel cells have numerous benefits which make them superior compared to the other technologies. The integration of the fuel cell system is to provide the continuous power supply to the load as per the demand. In the fuel cell energy system which is used for the distributed generation applications, the source is integrated with the DC – DC boost converter to stabilize the voltage from the fuel cell. The output of the boost converter is then fed to the three phase PWM inverter to get the three phase ac voltage for the grid connected applications.

II.FUEL CELLS

1. Basic of Fuel Cell:

The first references to hydrogen fuel cells appeared in 1838. In a letter dated October 1838 but published in the December 1838 edition of The London and Edinburgh Philosophical Magazine and Journal of Science, Welsh physicist and barrister William Grove wrote about the development of his first crude fuel cells. He used a combination of sheet iron, copper and porcelain plates, and a solution of sulphate of copper and dilute acid.[1-4][5] In a letter to the same publication written in December 1838 but published in June 1839, German physicist Christian discussed the first crude fuel cell that he had invented. His letter discussed current generated from hydrogen and oxygen dissolved in water.[6] Grove later sketched his design, in 1842, in the same journal. The fuel cell he made used similar materials to today's phosphoric-acid fuel cell. In 1939, British engineer Francis Thomas Bacon successfully developed a 5 kW stationary fuel cell. In 1955, W. Thomas Grubb, a chemist working for the General Electric Company (GE), further modified the original fuel cell design by using a sulphonated polystyrene ion-exchange membrane as the electrolyte. Three years later another GE chemist, Leonard Niedrach, devised a way of depositing platinum onto the membrane, which served as catalyst for the necessary hydrogen oxidation and oxygen reduction reactions. This became known as the "Grubb-Niedrach fuel cell". GE went on to develop this technology with NASA and McDonnell Aircraft, leading to its use during Project.

This was the first commercial use of a fuel cell. In 1959, a team led by Harry Ihrig built a 15 kW fuel cell tractor for Allis-Chalmers, which was demonstrated across the U.S. at state fairs. This system used potassium hydroxide as the electrolyte and compressed hydrogen and oxygen as the reactants. Later in 1959, Bacon and his colleagues demonstrated a practical five-kilowatt unit capable of powering a welding machine. In the 1960s, Pratt and Whitney licensed Bacon's U.S. patents for use in the U.S. space program to supply electricity and drinking water (hydrogen and oxygen being readily available from the spacecraft tanks). In 1991, the first hydrogen fuel cell automobile was developed by Roger Billings.

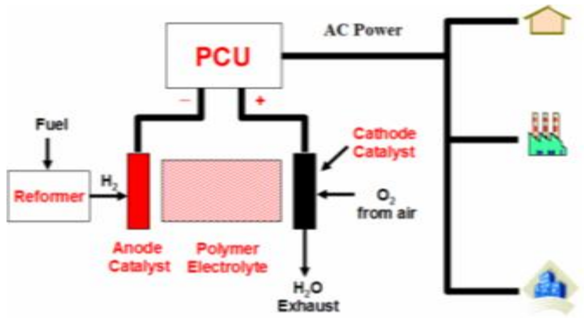

Figure 1. Fuel cell Internal Structure.

III.PROJECT OBJECTIVES

- Reduce The Production Cost Of Fuel Cell Systems To Be Used In Transport Applications, While Increasing Their Lifetime To Levels Competitive With Conventional Technologies,
- Increase The Electrical Efficiency And The Durability Of The Different Fuel Cells Used For Power Production, While Reducing Costs, To Levels Competitive With Conventional Technologies,
- Increase The Energy Efficiency Of Production Of Hydrogen Mainly From Water Electrolysis And Renewable Sources While Reducing Operating And Capital Costs, So That The Combined System Of The Hydrogen Production And The Conversion Using The Fuel Cell System Is Competitive With The Alternatives Available In The Marketplace;
- Demonstrate On A Large Scale The Feasibility Of Using Hydrogen To Support Integration Of Renewable Energy Sources Into The Energy Systems, Including Through Its use as a competitive energy storage medium for electricity produced from renewable energy sources;
- Reduce the use of the EU defined "Critical raw materials", for instance via low or platinum free resources and through recycling or reducing or avoiding the use of rare earth elements.

IV. LITERATURE REVIWE

Fuel cells based DG system is considered an alternative to centralized power plants due to their nonpolluting nature, high efficiency, flexible modular structure, safety and reliability. At present, they are under extensive research investigation as the power source of the future, due to their characteristics. A fuel cell converts chemical energy directly to electrical energy through an electrochemical process. As opposed to a conventional storage cell, it can work as long as the fuel is supplied to it. There are many motivations in developing this method of energy generation and it needs further development to have a realistic system analysis combining various subsystems and component.

Daniel et al (2015) from University of Maryland, college park, has analyzed hybrid systems of SOFC’s integrated with gas turbine engines. They have integrated SOFC’s with three different gas turbine engine types’ turbojet, combined exhaust turbofan and separate exhaust turbofan. Catalytic partial oxidation is used to produce fuel (hydrogen) for the SOFC. Thermodynamic analysis is carried out for CPOx reactors, SOFC and three gas turbines resulting in increased fuel efficiencies by 4% and 8% for 50kW and 90kW respectively hybrid power systems involving SOFC/ separate exhaust turbofan respectively. Similar results were shown for other gas turbine types. A parametric study on these hybrid systems show that the systems performance is dependent on operating fuel cell voltage, percent fuel oxidation, and SOFC assembly air flow. With these hybrid systems, fuel flow is reduced by 5% and electric power output is increased by ~500% without effecting TIT.

ZaharHajabdollahi and Pei-Fang (2016) from Huazhong University of science and technology, Wuhan, China have worked on optimization of a cogeneration plant including gas turbine, SOFC, heat recovery steam generator(HSRG) as well as inlet cooling system. Individual mathematical models of each component were verified with the experiment data from literature and results were observed to be in ~2% range. A probability is carried by varying a system’s design parameters like compressor & turbine efficiencies, Turbine inlet temperatures(TIT), fuel mass flow rate etc,. This study resulted in 5 optimum design points A-E. Point A shows maximum exergy efficiency of 0.4849 and worst total cost rate (TCR) i.e1044$/hr, whereas point E shows minimum TCR (734$/hr) with a lower exergy efficiency of 0.4590. Remaining points shows moderate values of both objectives. Design points A and B include SOFC where other points do not include it. Thus, adding a SOFC system to the gas turbines increases exergy efficiencies where the TCR grows worst.

Barelli et al (2016) from University of Perugia, Perugia, Italy worked on SOFC/ GT system integrated in Micro-Grids. They stated that SOFC/GT hybrid system efficiency performance increases with a mean efficiency of 54.5% on daily basis and its short time response and a wide load perturbations as low as 42.8% of hybrid systems full power. In their research work, SOFC-GT hybrid systems dynamic model is created with control strategy to regulate the SOFC and GT systems to the load demand with safe SOFC operation. With drop in load demand, SOFC's efficiencies increases slightly by 2% for a load drop from 95kW to 62.5kW. This shows that SOFC-GT hybrid system with a wellestablished control strategy is one of the efficient power generation system for high load demand fluctuations.

Penyarat (2015) from King Mongkut's University of Technology North Bangkok, Thailand have worked on two different configurations of the SOFC-GT hybrid systems. For one of the configuration, fuel exchanger's hot stream is drawn from combustor and other from turbine exit. First configuration results in higher SOFC operating temperature and lower Turbine inlet temperature vice versa for the second configuration. First hybrid system's overall efficiencies are ~4.5% higher than second one. This is due to the higher operating temperature of SOFC system where as GT efficiency is higher in second configuration.

McLarty et al (2013) from University of California worked on integration of fuel cells with gas turbines. They have come up with molten carbon fuel cell and SOFC hybrid systems with Gas turbines. Steady state models for each hybrid systems are created and analyzed. Both the hybrid systems are assumed with cathode recirculation to increase the inlet air temperatures. These hybrid systems can produce up-to 1.2 MW electric power with LHV efficiencies higher than 70% and 75% respectively. This study shows that SOFC-GT hybrid systems are more efficient in terms of fuel LHV. McLarty et al also worked on dynamic models of the hybrid systems with additional control methods.

Massardo&Lubelli (1999) developed four different hybrid cycle configurations of SOFC’s plus internal reforming integrated with gas turbines. Numerical thermodynamic models were modeled to understand the impact of anode and cathode inlet temperatures on thermos cycles.

Campanari& Iora (2004) analyzed hybrid cycle of micro gas turbine integrated with SOFC. Hybrid cycles analysis results showed an overall electrical energy efficiency increased to 63% and when SOFC is used as CHP system, thermal efficiency increased to 86%. A similar study by Haseli (2008) on SOFC hybrid cycles, with on additional air and fuel recuperates increased energy and exergy efficiencies to 60.6% and 57.9% respectively.

Mehrpooya et al (2014) compared cross and co-flow planar SOFC hybrid systems and observed that both the configuration delivered similar results. A further parametric analysis of the model resulted in increase in power output with inlet temperature and pressure of SOFC stack.

V.EXPECTED FUEL SYSTEM PARAMETER

Fuel cells are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided. The hydrogen can be supplied directly, or indirectly produced by reformer from fuels such as natural gas, alcohols, or gasoline. Each unit ranges in size from 1-250 kW or larger MW size. Even if they offer high efficiency and low emissions, today’s costs are high. Phosphoric acid fuel cell is commercially available in the range of the 200 kW, while solid oxide and molten carbonate fuel cells are in a pre-commercial stage of development. The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. The recent research work about the fuel cells is focused towards the polymer electrolyte membrane (PEM) fuel cells. Fuel cells in sizes greater than 200 kW, hold promise beyond 2005, but residential size fuel cells are unlikely to have any significant market impact any time soon.

1. Features:

- Size: 1 kW – 10 MW
- Efficiency: electricity (30 – 60%), cogeneration (80 – 90%)
- Installed cost ($/kW): 1,000 – 5,000
- O&M cost ($/kWh): 0.0019 – 0.0153
- Fuel: natural gas, hydrogen, propane, diesel
- Emission: very low
- Cogeneration: yes (hot water, LP or HP steam)
- Commercial Status:
- PAFC: commercially available
- SOFC, MCFC, PEMFC: available in 2004

Many different materials can be used for the realization of a traditional bipolar plate however some requirements must always be guaranteed:

- Functionality of the electrical connection between two consecutive cells;
- a constant and homogeneous supply of hydrogen and oxygen to the electrodes of the different cells;

- An efficient thermal dissipation;
- The removal of the water produced by the reactions.
- Figure (5.1)Block diagram of fuel cell system.

2. Applications:

- PAFC: medical, industrial, schools, commercial utilities, utility power plants,
- waste water treatment plants
- SOFC: residential cogeneration, small commercial buildings, industrial facilities
- MCFC: industrial, government facilities, universities, hospitals
- PEMFC:
- Automotive
- Residential (< 10kW), both with and without cogeneration
- Commercial (10 – 250kW), both with and without cogeneration
- Light industrial (< 250kW), both with and without cogeneration
- Portable power (< several kW)

3. Advantages:

- PAFC: quiet, low emissions, high efficiency, proven reliability
- SOFC and MCFC: quiet, low emissions, high efficiency
- PEMFC: quiet, low emissions, high efficiency, synergy with automotive
- PEMFC Advantages and Disadvantages Advantages of the PEMFC are as follows [6]:
- The power density of the cell stack is very high, particularly in pressurized systems.
- The operative pressure difference between the anode and the cathode can be very large due to the mechanical properties of the solid polymer electrolyte. Therefore, operating with a pressurized system it is quite easy.
- A wide variety of cell component materials can be adopted on account of its low operating temperature (80 °C). In particular, use of low cost carbon materials may contribute to the cost reduction of cell stack. On the other hand, the PEMFC technology shows the disadvantages listed below [7]:
- PEMFC catalysts are susceptible to CO poisoning due to their low operating temperature. Therefore, the CO concentration has to be reduced below 10 ppm with CO removal if the reformate from hydrocarbons or alcohols is used as a fuel for the PEMFC.
- The temperature of recovered waste heat is lower than that of other fuel cells. As a result recovered heat can be utilized only as hot water.
- The water management of the membrane electrolyte is very important for the cell performance, because it secures the appropriate amount of water to show its sufficient ionic conductivity. On account of these features, PEMFC development for electric vehicle and portable power applications still needs more time. The PEMFC technology is also promising for residential cogeneration systems if combined with smallscale natural gas fuel processors.

4. PEMFC Applications

PEM Fuel cells can generate power from some W to hundreds of kW. Because of this, they may be used in almost every application where local electricity generation is needed. PEMFC are already being tested inside applications such as automobiles, buses, utility vehicles, scooters, bicycles, aerospace/military applications (e.g. Shuttle and submarines). PEMFC are also being tested for distributed power generation inside individual homes, buildings or communities due to their modularity and excellent flexibility in power supply [8,9,10]. PEMFC fuel cell used for different applications have at the same time different configurations whose characteristics change in order to achieve the requirements needed by the different environments in which they are involved. This document will now analyze the three most important application environments for PEM fuel cells which are the followings:

- Transportation (up to 70 kW);
- Stationary power applications (up to 500 kW)
- Portable power applications (up to some kW

Applications for Transportation and Automotive Sector Transportation is a competitive and promising sector for PEMFC fuel cells due to two factors:

- The future expected deplete of fossil fuels;
- The possibility to guarantee environment friendly vehicles.

The development of a Fuel Cell Vehicle (FCV) requires the on-board integration of a fuel-cell system and electric energy storage devices with an appropriate energy management system. Actually most of the major car makers and the governments of some states (like USA and JAPAN) are actively engaged in the development of FCVs [11]. However the most important factor for the success of a FCV is the success of the hydrogen economy and its related technology.

It is a fact that FCV systems equipped with directconversion fuel processors (which is the most secure FCV technology since it does not imply the storage of hydrogen that can easily cause an explosion) can successfully compete with conventional Internal Combustion Engine (ICE) vehicles in all aspects except for the cost and maintenance [12,13]. However direct conversion fuel processors are hybrid systems (which converts fuels into hydrogen and then into energy with fuel cells) that requires great spaces inside vehicles and a complex feedback control system. The consequence is that actually they are integrated only inside bigger vehicles like buses which have more space to house the fuel processor. The main requirements that the automotive PEM stack technology still needs to fulfill in order to became a major technology on the market are:

- A very short start-up time (fraction of a minute);
- Small size and weight of the PEMFC systems;
- An operating life time which spans from 3000 to 5000 operational hours.

Stationary Applications for Distributed Power Generation Distributed power generation is another sector in which PEMFC developments holds great interest. The high modularity, high efficiency and lower emission of PEMFC stacks allow their use for the expansion of the electric network. As a result part of the loads of the network can be directly managed by many power systems which are distributed inside different types of buildings and structures, thus lowering the burden placed on the power plants. Stationary fuel cells for distributed generation could be used inside in many different places [2]:

- As the main power source in places not reached by the electric power grid;
- As supplemental power source working in parallel with the electric grid;
- As complementary power source in power systems based on renewable energy like photovoltaic and wind turbines (thus generating power when these energy sources cannot meet the demand);
- As emergency power generators to cover the malfunctions of the electric grid; The requirements that these systems have to fulfill are:
- A lower noise level since the power unit are usually installed indoor;
- Short start-up time for emergency power systems;
- Power units designed for outdoor use must be able to operate in extreme ambient conditions;
- An operational life cycle which spans from 40,000 to 80,000 hours (five to ten years).
- Applications for Portable Power Systems Portable power systems based upon PEMFC technology consists in 2 main types of applications [2]:
- Power cells for battery replacements with power below 100 W;
- Portable generators with at least 1 kW power based on power cells;

The main factors that must be considered in those systems are:

- The operative time of the battery;
- The size and weight of the system.

Power units with significantly higher power densities or larger energy storage capacities are suited for applications like portable computers, communication and transmission devices, power tools, remote meteorological or other observation systems. PEMFC detains many advantages like fast startup, simplicity of operation, zero emissions, and potential for low capital and maintenance costs that have attracted many interest regarding DG (Distributed Generation) applications [14]. There is however one major problem in the use of this types of fuel cells for the those applications: the need to refuel them with hydrogen. Due to its characteristics, hydrogen is a gas that has both a low ration of energy per volume of gas stored (thus requiring large storage spaces) and an high penetration in solid materials which means that the gas escapes on the storage device on normal conditions. In order to minimize storage spaces and to ensure that it remains inside the storage device, the hydrogen have to be highly pressurized. However pressurization is a process that requires energy and that increases the magnitude of an eventual explosion. Another problem which prevents portable PEMFC to be used inside military environments is that the cells are easily detectable by enemy sensors.

VI.CONCLUSIONS

Hydrogen and fuel cell technology have advanced considerably over the last fifteen years. At the global level, this area continues to face significant challenges—technical, commercial and infrastructure-related—that need to be overcome before fuel cells can realize the full potential of which they are capable. Policy makers have included hydrogen and fuel cell on the map of future energy strategies and have already taken into account the fact that fuel cells have great real potential and can successfully meet the technical, social, economic and environmental objectives in the context of the multidisciplinary concept of sustainable development. In this paper, the review of literature and agencies' reports on specialized metrics in the domain of the hydrogen fuel cell technologies, highlights the essential considerations regarding stationary applications, as follows:

- More than 850 MW of large stationary fuel cell systems with a (> 200 kw) nominal power have been installed worldwide for power generation and CHP applications up until 2018.
- Worldwide, the use of three types of fuel cell technologies is prevalent: MCFC, SOFC and PAFC.
- AFC and PEMFC are relatively new technologies under development and implementation within stationary applications.
- The main modalities of integrating hydrogen fuel cell technology into stationary applications are in the form of CHP units with fuel cells for small individual residential buildings, back-up power systems and large capacity electric power stations or distributed generation systems.
- The key factors that influencing development include: energy and climate policies, fuel cell funding programmes, concurrent technologies, the attendance of fuel cell system producers and energy costs.

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