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Implementation of Solar Cells and Natural Gas Fuel Cells as a Green Hybrid Power Plant

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Abstract

Global warming is a major concern in today's world. To address this issue, most countries are working on the usage of renewable energy sources like solar energy, clean fuels (hydrogen) and trying to increase the efficiency of fossil fuel plants. This paper discusses the hybridization of the renewable solar energy source with highly efficient and clean usage of natural gas fossil fuel. The hybrid power plant used in this project uses renewable energy sources as a reliable power supply with stand-alone and grid-connected capability which can increase network power quality. Simulation results have been discussed to show the contribution of natural gas fuel cells, photovoltaic power plants, and electric energy storage in supplying a constant load.

Keywords: *Hybrid power plant, solar cell, fuel cell, natural gas.*

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INTRODUCTION

A green hybrid power plant (GHPP) hybridizes solar energy as a renewable energy source and hydrogen fuel cells from natural gas. The system efficiency can be improved by using power electronics technology and also by supporting it with electric energy storage as shown in Figure 1. This paper introduces an effective solution for the global warming effect by hybridization of a renewable energy source (solar energy) with highly efficient and clean usage of fossil fuel (natural gas). Other effects of this hybrid power plant include using the renewable energy sources as a reliable power supply with stand-alone and grid-connected capability which can increase network power quality. It also introduces knowledge about usage of renewable energy sources and hydrogen as a clean energy source.

Solar energy is one type of renewable energy sources which can be converted easily and directly to electric energy by photovoltaic converters. Photovoltaic converters are important converters for the application of renewable energy sources because of the direct conversion of solar energy to electric energy. They have some advantages such as low weight and feasibility of small scales, silent energy conversion without any environmental effects, long life, and installation capability from small power (watt) to large power (megawatt) scales.

This technology converts natural gas into electricity to provide a quiet, clean, and highly efficient on-site electric generating system and thermal energy source that can reduce facility energy service costs by 20 to 40% over conventional energy service. A green hybrid power plant consists of the following main parts as shown in Figure 2:

- Solar power plant (photovoltaic technology) [1, 13].
- Natural gas fuel cell (fuel cell technology with fuel reformer) [2].
- Electrical energy storage (rechargeable battery bank).
- Power conditioning unit (power electronics and control) [3].

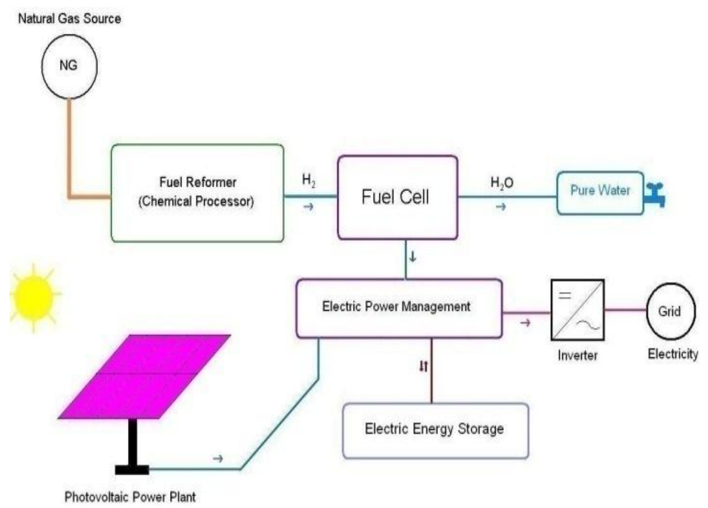

Fig. 1: *Green Hybrid Power Plant.*

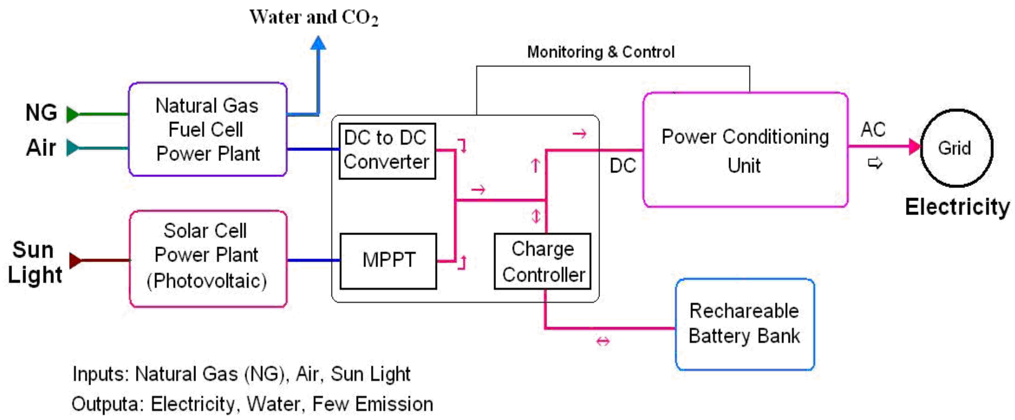

Fig. 2: *Block Diagram of a Green Hybrid Power Plant.*

SOLAR POWER PLANT

Solar energy is one type of renewable energy sources which can be converted easily and directly to electric energy by photovoltaic converters. The process of non-movable mechanisms to convert solar energy to electric energy is called photovoltaic phenomenon, whereas the conversion device is called a solar cell. Solar cells convert the energy of light's photons to electric energy with efficiency between 5 to 25% without using a thermodynamic cycle or an active fluid. Solar cells can be light collectors directly or can use light concentrators like mirrors or convex lenses.

This photovoltaic converter is a developed energy converter with advantages such as relevant design and installation, silent energy conversion, long life time with less maintenance requirement, and easy transportation and light weight. However, in comparison with other types of energy converters like diesel generators, it is more expensive. Therefore, the optimum operation and the maximum energy absorption from solar cells are important factors [1, 2].

The solar power plant consists of some solar trackers which depend on the solar power plant's output with some photovoltaic panels. They follow the sun during the day and generate electricity directly. By using solar trackers, it is possible to increase the energy efficiency by 40% in comparison with the fixed solar arrays. To increase the efficiency of a photovoltaic power plant, some special power management systems like solar trackers with maximum power point should be used [1]. Figure 3 shows a typical photovoltaic power plant where the details will be explained in the next sections.

Effects of the Sun Radiation Angle on the Solar Cell Output

Using movable photovoltaic arrays to follow the Sun during the day and providing a condition in that the solar light directly radiates on the solar cells will optimize energy conversion. In a photovoltaic converter, the energy of absorbed photons is converted to electric energy by solar cells. Therefore, the output of electric power depends on the radiation angle of sunlight. The electric characteristics of solar cells change due to the variation of the generated electrons with light intensity. Figure 4 shows the current-voltage characteristic of a sample solar cell.

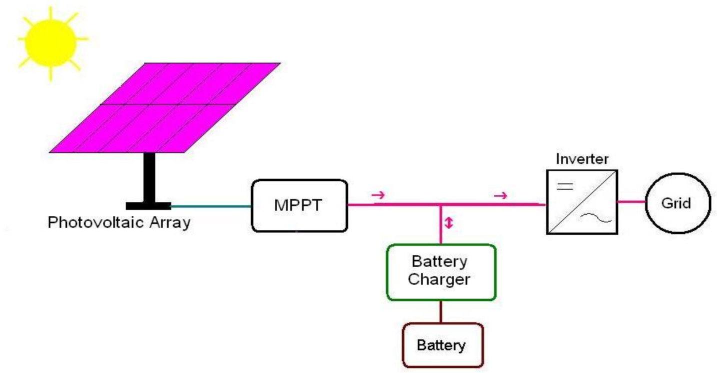

Fig. 3: *A Typical Photovoltaic Power Plant Configuration.*

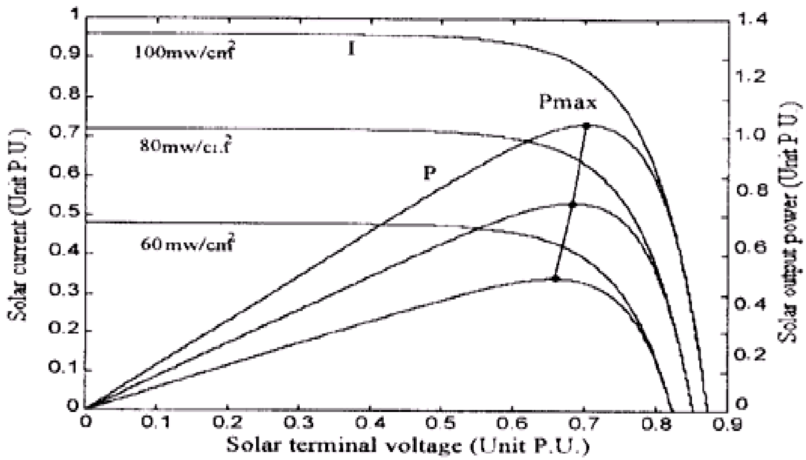

Fig. 4: *Variation of a Solar Cell Output Characteristics with Light Intensity Changes* [6].

The generated current by solar cells varies according to light intensity changes. Furthermore, it can be observed that the maximum power point of output power changes by variation of insulation of light and the operating temperature. Thus, it is necessary to track this point to deliver the maximum available power to load [5]. As a result, the output power of the solar cell and the photovoltaic array can generate electric power less than its nominal power.

Due to the motion of the Sun during the day, sunlight radiates on the surface with different angles and it is not perpendicular for a fixed PV-array, whereas it can be designed to be always perpendicular for a movable array with full degree of motion. Because of high cost of the solar array, where the angle between solar radiation and collector surface affects energy absorption, it is important to provide some conditions to absorb the maximum solar energy and then convert it to electric energy for optimum converter operation. Because of the low efficiency of the solar cells (less than 12%) and due to their higher price in comparison with other energy converters, it is important to absorb and convert the maximum electric energy from the PV-array.

Moveable Photovoltaic Arrays

In contrast with a fixed PV-array, the solar collector (or PV-array) which follows the Sun's motion, can receive the maximum radiation and generate optimum energy because sunlight radiates perpendicularly on the surface of the solar cells. The result of using this kind of PV-array increases the input of solar energy [1]. In Figure 5, the output powers of tracking and fixed sample photovoltaic array are compared. The energy increasing for a photovoltaic converter with tracking PV-array is about 40% yearly, which is significant.

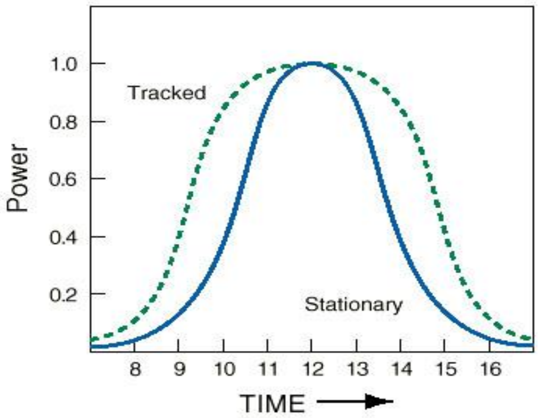

Fig. 5: *Tracked Photovoltaic Panel Output Power in Comparison With Fixed One*.

NATURAL GAS FUEL CELL POWER PLANT

Natural Gas Fuel Cell

Natural gas fuel cell (NGFC) is a promising new technology that is simple and reliable. It improves natural gas utilization and efficiency. This technology converts natural gas into electricity which provides a quiet, clean, highly efficient, and on-site electric generating system and a thermal energy source that can reduce facility energy service costs by 20–40% over conventional energy service. In practice, fuel cells result in very low emission of harmful pollutants, and the generation of high quality, reliable electricity. Most common fuel fells use hydrogen as fuel as hydrogen can be generated from any other fuel that contains hydrogen molecules like gasoline, methanol and natural gas. The fuel reformer generates hydrogen in a chemical processing unit, and can feed the fuel cell to generate electricity and water. Figure 6 shows the primary subsystems of an NGFC system. The input of the system is natural gas and air. The output of this system is electric power, water and heat (which will be used in a fuel processor unit). An NGFC is reliable to improve natural gas utilization and efficiency. This technology converts natural gas into electricity that provides a quiet, clean, and highly efficient on-site electric generating system and thermal energy source which can reduce energy service facility cost by 20–40% over conventional energy service.

Fuel cells powered by natural gas are an extremely exciting and promising new technology for the clean and efficient generation of electricity. Fuel cells have the ability to generate electricity using electrochemical reactions as opposed to combustion of fossil fuels to generate electricity. Essentially, a fuel cell works by passing streams of fuel (usually hydrogen) and oxidants over electrodes that are separated by an electrolyte. This produces a chemical reaction that generates electricity without requiring the combustion of fuel, or the addition of heat as is common in the traditional generation of electricity. When pure hydrogen is used as fuel, and pure oxygen is used as the oxidant, the reaction that takes place within a fuel cell produces only water, heat, and electricity [7–9].

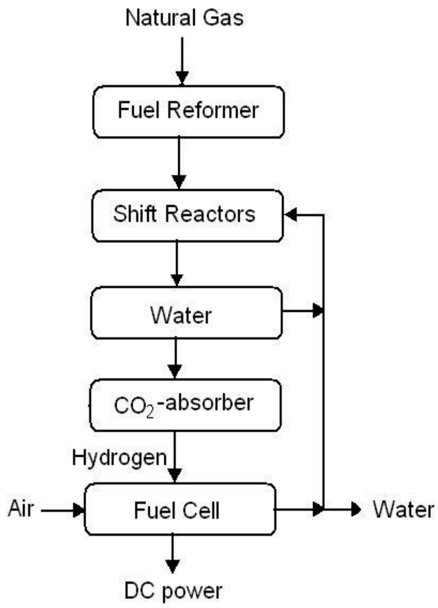

Fig. 6: *Natural Gas Fuel Cell System.*

Benefits of Natural Gas Fuel Cells

The generation of electricity has traditionally been a very polluting, inefficient process. However, with the new fuel cell technology, the future of electricity generation is expected to change dramatically in the next ten to twenty years. Research and development into fuel cell technology is ongoing to ensure that the technology is refined to a level where it is cost effective for all varieties of electricity generation requirements.

Fuel cells provide the cleanest method of producing electricity from fossil fuels. While a pure hydrogen, pure oxygen fuel cell produces only water, electricity, and heat, fuel cells in practice emit only trace amounts of sulfur compounds and very low levels of carbon dioxide. However, carbon dioxide produced by fuel cell use is concentrated and can be readily recaptured, as opposed to being emitted into the atmosphere. In addition to electrical benefits of NGFC like clean electricity, distributed generation, and high efficiency [10], they also have many environmental benefits as follows.

Some environmental benefits of natural gas fuel cells are as follows:

- A 70% reduction in carbon dioxide (a greenhouse gas) emissions compared with a new coal-fired power plant and a 23% reduction over a conventional natural gas-powered combined-cycle plant.
- A reduction in nitrogen oxide (the primary contributor to ozone or smog) emissions, i.e., 85% less than the ultra-tight limits set in the Los Angeles area.
- Virtual elimination of sulfur dioxide (the primary contributor to acid rain) emissions and particulate matter.
- No solid waste discharges or negative impact on surrounding water quality, and no water consumption [11].

Fuel cells are classified primarily by the type of electrolyte they employ. This determines the chemical reactions that take place in the cell, the catalysts required, the temperature range in which the cell operates, the fuel required, and other factors. A few of the most promising types include:

- Proton exchange membrane fuel cell (PEM)
- Phosphoric acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)
- Alkaline fuel cell (AFC)
- Direct methanol fuel cell (DMFC)

GREEN HYBRID POWER PLANT REQUIREMENTS

Electric Energy Storage

The response of NGFC to provide enough electricity by increasing the demand involves delay because fuel processing and electricity generation is a chemical reaction. Figure 7 shows the response time of a sample fuel reformer with different response time characteristics (the assumption is that one molecule of input fuel converts to three molecules of hydrogen) [11].

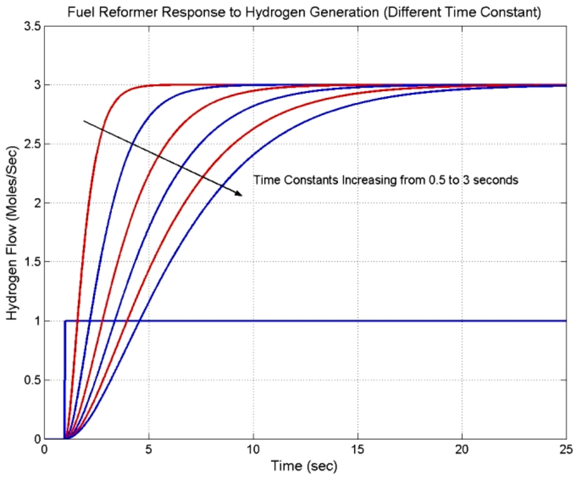

Fig. 7: *Different Response Time of Fuel Reformer to Increase in Hydrogen Demand.*

According to the characteristics of the fuel reformer and hydrogen demand for fuel cells (increasing power of fuel cells), the response time delay can be significant. Therefore, it is necessary to have energy storage to eliminate the effect of this delay from electricity output of the power plant and increase the power quality. Also, electricity from a solar power plant can be generated only during sunny days whereas continuous electric energy is needed 24/7. Therefore, energy storage is also needed for a solar power plant. This storage can be a deep-cycle lead acid battery, flywheel or an ultra-capacitor.

Stabilization of Renewable Energy Sources

To help renewable technologies like wind turbines, photovoltaic converters, and natural gas fuel cells become more competitive with fossil and hydroelectric power plants, their output can be stabilized with the use of energy storage systems. Energy storage systems can be used to follow loads, stabilize voltage and frequency, manage peak loads, improve power quality, defer upgrade investments, and support renewable energy sources.

Power Conditioning Unit

The power conditioning unit combines the electric energy from the solar and fuel cell power plants throughout the electric energy storage system. The output of the power plant should have specific synchronized voltage and frequency levels to be able to connect to the power grid and also includes different types of control and protection systems. The power conditioning unit could consist of several components:

- DC/DC converter: This type of converter switches power electronic circuits with high efficiency and are used to increase or decrease output voltage to adapt output voltage and control DC electric power flow. In this power plant, both the fuel cell and the solar cell output voltages vary as a function of both load and sunlight. Therefore, each one of these power plants requires a DC/DC converter to generate a constant low voltage DC output voltage.
- DC to high-frequency AC converter: The low voltage DC bus needs to be boosted up and then converted to AC to be connected to the utility grid.
- High frequency isolation transformer: The high frequency low-voltage AC will be increased using a step-up high-frequency transformer.
- AC/DC rectifier: The high-frequency AC voltage which is also boosted by a high-frequency isolation transformer of the previous steps is rectified to generate high-voltage DC voltage.
- DC/AC inverter: The high-voltage DC of the previous step is rectified to generate AC voltage to be connected to the utility grid.
- Supervisory control using a digital signal processor board.

CASE STUDY AND SIMULATION RESULTS

One method to increase the output power quality of the renewable energy converters related to Qatar environment is to hybridize them with energy storage units as mentioned in the previous section. A case study has been done to show the effects and benefits of hybridization of renewable energy converters and to show the quality of power delivered to the load [1, 2, 12].

The corresponding hybridized system is the green hybrid power plant that is shown in Figure 2. The converters of the solar power plant and fuel cell are boost converters, whereas the converter of the battery is a bidirectional boost-buck converter. A bi-directional DC-DC converter has been used for battery storage since it should be charged whenever the required power for the load is less than the nominal power and when the SOC of the battery is low. It has been assumed that the time constant of the natural gas fuel cell is about 0.5 s and the solar panel starts to work at t = 1.5 s where the power plant supplies a 1 kW resistive load. In practice, the time constant of the fuel cell is much longer than this, but in simulation it has been chosen as 0.5 s. From t = 0 to t = 0.5 s, battery is the only source which can supply the load. At t = 0.5 s, fuel cell has reached its nominal power and it can supply the load. At t = 1.5 s, when there is enough light that the photovoltaic panel can provide required energy, the fuel cell is turned off and solar cells feed the load.

Figures 8 and 9 show the voltage of the fuel cell and current of the photovoltaic panel, respectively. Figure 10 shows the battery output current during this period. The load receives energy from the battery before the fuel cell becomes ready to provide energy for the power plant and when the output of the photovoltaic panel is low. When the output voltage of the fuel cell rises enough, the energy conversion starts in this unit and provides energy to the load as shown in Figure 11. The output voltage of the load which is regulated in order to supply a continuous energy to the load [12, 13].

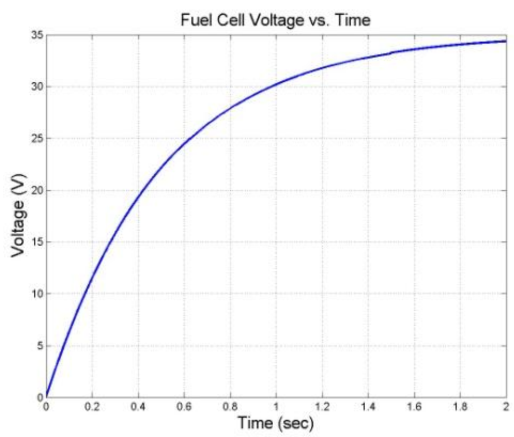

Fig. 8: *Fuel Cell Startup with Exponential Dynamic Model.*

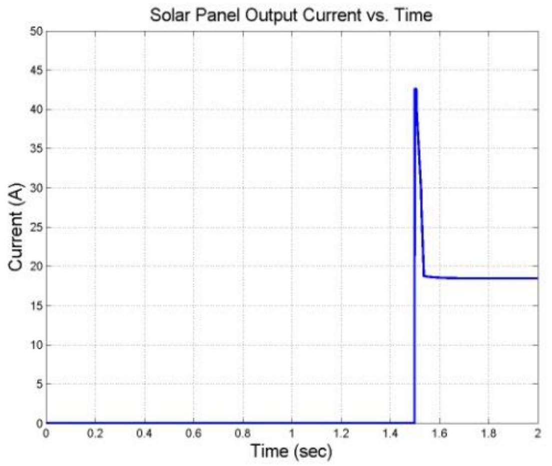

Fig. 9: *Solar Power Plant Output Current (starting at t = 1.5 s.*

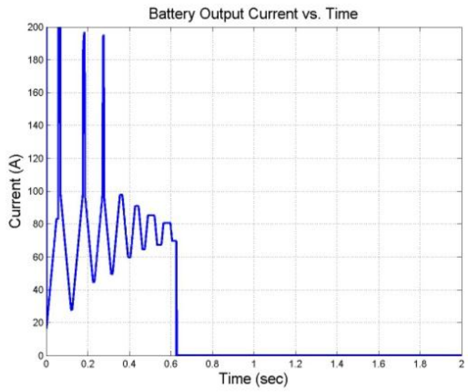

Fig. 10: *Battery Current Wave Form during Load.*

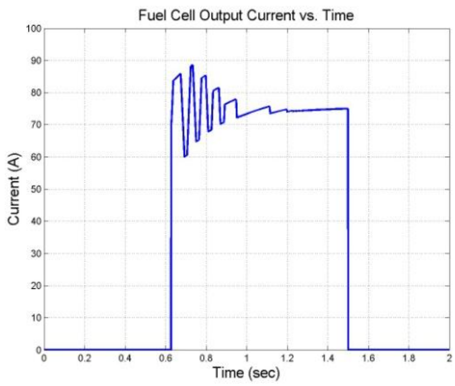

Fig. 11: *Fuel Cell Current Wave Form during Power Generation for Load.*

CONCLUSIONS

Global warming and environment issues should be addressed by each country in order to effectively prevent environmental damage. One major solution for global warming is the use of renewable and pollution-free energy for power plants. Increasing the efficiency of fossil fuel power plant can help decrease pollution caused by the use of the fossil fuel power plants. In addition, using the new technologies like fuel cells can help in decreasing pollution. In this paper, producing hydrogen from natural gas (as a fossil fuel) and using it for fuel cells power plant was investigated. The output power of a solar power plant with either a fixed or a movable array was investigated and the results of movable and fixed arrays were analyzed. To have a more reliable and more efficient power plant, the solar cells and fuel cells power plants were combined as a Green Hybrid Power Plant using power electronics and energy storages. The study showed that an effective power conditioning system can improve the output power quality.

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