Hybrid Fuel-Cell Strategies for Clean Power Generation

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***Abstract*—A hybrid power system consists of a combination of two or more power generation technologies to make best use of their operating characteristics and to obtain efficiencies higher than that could be obtained from a single power source. Since fuel cells directly convert fuel and an oxidant into electricity through an electrochemical process, they produce very low emissions and have higher operating efficiencies. Hence, combining fuel cells with other sources, the efficiency of the combined system can be further increased or extend the duration of the available power to the load as a backup power. In this paper, different types of fuel-cell hybrid systems and their applications are presented. An analysis of the combined cycle operation of a solid oxide fuel cell (SOFC)–microturbine is presented. A strategy for combining the thermophotovoltaic power generation unit and SOFC to obtain the hybrid power system that would have higher efficiency is proposed. The hybrid operation of wind power and solar power system with proton exchange membrane fuel cell is also presented.**

***Index Terms*—Fuel cell, hybrid power systems, solar power, thermophotovoltaic (TPV) system, wind power.**

I. Introduction

FUEL CELLS are widely recognized as one of the most promising technologies to meet the future power generation requirements. Since fuel cells directly convert fuel and an oxidant into electricity through an electrochemical process, they can achieve operating efficiencies approaching 60%—nearly twice the efficiency of conventional internal combustion engines. Fuel cells produce very low levels of pollutant emissions (NO_x, SO_x, and CO_2). There are several types of fuel cells, distinguished by the type of electrolyte material used, as shown in Table I [1].

Proton exchange membrane (PEM) fuel cells are gaining importance as the fuel cell for vehicular applications because of their low operating temperature, higher power density, specific power, longevity, efficiency, relatively high durability, and the ability to rapidly adjust to changes in power demand. The PEM is more suitable for automotive applications for the following reasons [2].

- PEM fuel cells can be started easily at ordinary temperatures and can operate at relatively low temperatures, below 100 °C.
- Since they have relatively high power density, the size could be smaller. Hence, they could be easily packaged in the vehicles.
- Because of the simple structure compared to other types of fuel cells, their maintenance could be simpler.
- They can withstand the shock and vibrations of the automotive environment because of their composite structure.

The PEM system has the following disadvantages.

- A PEM fuel cell requires pure hydrogen as the fuel, thus complicating the design of the reformer system.
- Any small amount of carbon monoxide in the fuel will poison the electrodes, resulting in severe degradation of performance.
- As there is a continuous generation of water at the cathode and also the requirement of a certain level of humidification, a sophisticated water management system is required.
- Platinum metal is required to coat the electrodes to enhance the reactions. Because of the higher cost of platinum, the PEM system is relatively expensive.

High-temperature solid oxide fuel cells are particularly suitable for automotive auxiliary power unit (APU) and stationary power generation applications. The advantages of the solid oxide fuel cell (SOFC) system are as follows [1]–[3].

- The fuel processor requires a simple partial oxidation reforming process that eliminates the need for an external reformer.
- It has less stringent requirements for reformate quality and uses carbon monoxide directly as a fuel. Hence, a sophisticated reformer is not required.
- It operates at extremely high temperatures of the order of 700 °C–1000 °C. As a result, it can tolerate relatively impure fuels, such as those obtained from the gasification of coal.
- Waste heat is high grade, allowing for smaller heat exchangers and the possibility of cogeneration to produce additional power.

TABLE I
FUEL-CELL TYPES AND OPERATING TEMPERATURES

Fuel Cell Type	Operating Temperature
Proton Exchange Membrane (PEM)	80° C
Alkaline fuel Cell	100° C
Phosphoric Acid Fuel Cell	200° C
Molten Carbonate Fuel Cell	650° C
Solid Oxide Fuel Cell (SOFC)	800° C -1000° C

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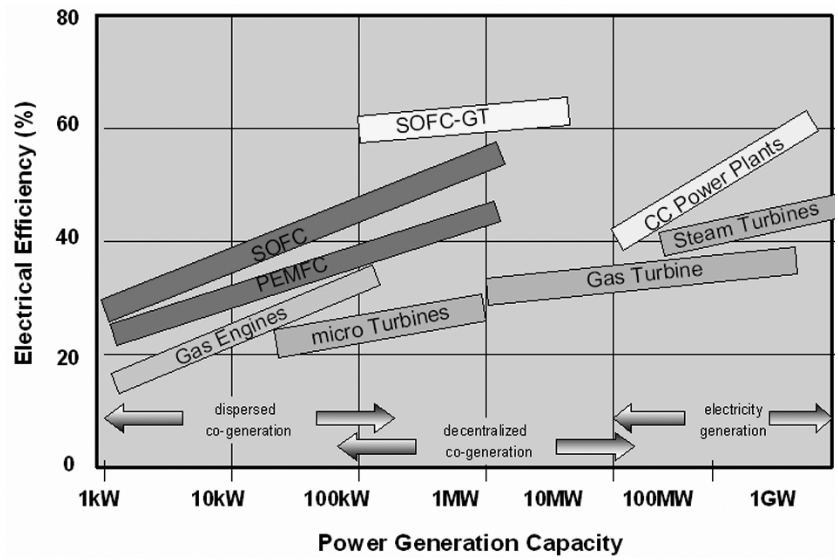

Fig. 1. Efficiencies of various power generation technologies.

- Water management is not a concern because the electrolyte is solid state and does not require hydration. The byproduct is steam rather than liquid water, hence, no need for water management.
- The SOFC does not need precious metal catalysts.

The disadvantages of the SOFC system are the following.

- Because of the high-temperature operation it is of the order of 20–30 min. Hence, the SOFC is not suitable for propulsion applications.
- Packaging of the low-temperature electronics and the high-temperature stack within the same enclosure is a major challenge.

The power densities of both PEM and SOFC systems are of the order of about 500 mW/cm^2 under typical operating conditions. The peak power densities under idealized conditions have been reported to be greater than 1000 mW/cm^2. The relatively simple design (because of the solid electrolyte and fuel versatility), combined with the significant time required to reach operating temperature and to respond to changes in electricity demand, make the SOFC suitable for large to very large stationary power applications. The startup time for the SOFC is of the order of 30–50 min, whereas the PEM system could be started in less than 1 min. Hence, the SOFC is not suitable for propulsion applications. However, as an APU in transportation applications and in stationary power generation systems, the starting time of the SOFC is not a major issue.

In this paper, the strategies for combining the fuel cells with other power generation technologies are discussed. Although it is possible to use all the above types of fuel cells in hybrid power systems, only the PEM fuel cell and SOFC, which are most developed, are considered in this paper. The hybrid power systems are classified based on their operation. An analysis of the combined cycle operation of an SOFC–microturbine is presented. A strategy for combining the thermophotovoltaic (TPV) power generation unit and SOFC to obtain the hybrid power system that would have higher efficiency is proposed. The hybrid operation of wind power and solar power system with PEM fuel cell are also presented.

II. Hybrid Fuel-Cell Systems

A hybrid power system consists of a combination of two or more power generation technologies to make best use of their operating characteristics and to obtain efficiencies higher than that could be obtained from a single power source. Hybrid fuel-cell systems are power generation systems in which a high-temperature fuel cell is combined with another power generation technology [4], [5]. The resulting system exhibits a synergism in which the combination has far greater efficiency than could be provided by either system operating alone [1], [6]. The efficiencies across a broad power range for various power generation technologies are shown in Fig. 1. As an example, combining SOFC or molten carbonate fuel cell with the gas turbine would increase the overall cycle efficiency while reducing per-kilowatt emissions. In some systems, combining fuel cells with wind or photovoltaic systems would extend the duration of the available power, which is of significance, rather than the overall efficiency. This type of system is used as a backup power or as an energy storage system. Getting higher efficiencies combined with low emissions, hybrid systems are likely to be the choice for the next generation of advanced power generation systems. These systems are not only used for stationary power generation, but also find application in transportation systems.

In this paper, the hybrid fuel-cell systems are classified as Type-1 and Type-2 systems. In a Type–1 system, a high-temperature fuel cell is combined with another power generation technology to increase the combined efficiency of the system. Examples of Type–1 systems include fuel cell with gas turbine, fuel cell with reciprocating (piston) engine, and designs that combine different fuel-cell technologies. In Type–2 hybrid systems, a fuel cell and another power generating system are combined to best make use of the operating characteristics of the individual units to either extend the duration of the availability of power or to supplement the fuel-cell power. Examples of Type–2 hybrid systems are combining a fuel cell with wind power or solar power. The Type–1 systems are mainly combined cycle operating systems. The Type–2

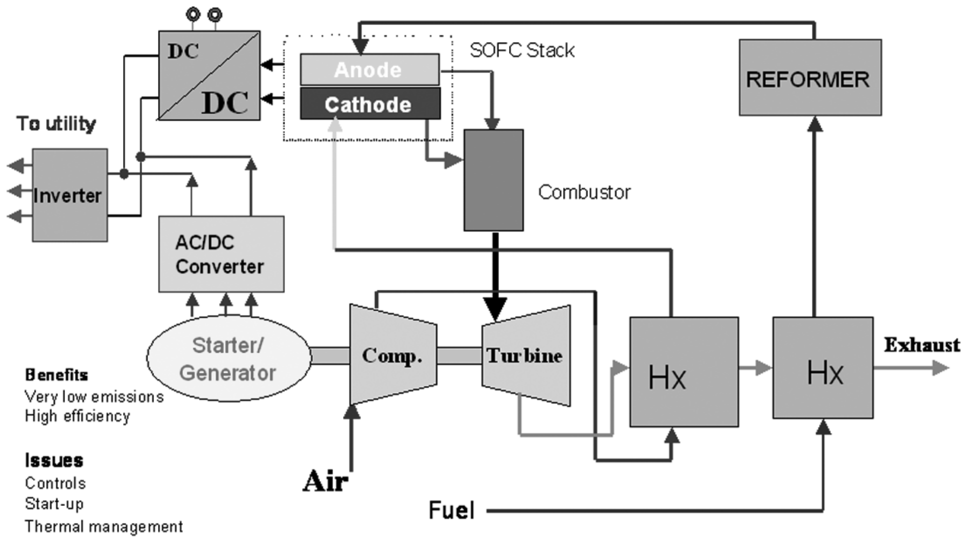

Fig. 2. SOFC–gas turbine hybrid system.

systems are mainly backup/peak shaving power systems. In this paper, the following hybrid technologies are discussed:

- high-temperature SOFC–gas turbine system (Type 1);
- SOFC–TPV system (Type 1);
- PEM fuel cell–solar power hybrid system (Type 2);
- PEM fuel cell–wind power system (Type 2).

III. High-Temperature SOFC–Turbine Systems

The hybrid power systems based on high-temperature fuel cells and gas turbines have been extensively analyzed and studied over the past several years by various universities, industries, and the U.S. Department of Energy for stationary power generation applications [7]–[15]. Successful development and commercialization of fuel cell/turbine hybrid power generation will allow the following:

- extremely high efficiency compared to other fossil fuel systems;
- ultralow emissions without additional cleanup;
- siting flexibility with environmentally friendly energy systems;
- fuel flexibility.

The SOFC–microturbine hybrid systems are also being investigated for use as APUs in commercial airplanes to provide the power to all the electrical loads [16], and in railroad vehicles to provide the power to all the accessory loads. Combination of a high-temperature fuel cell with a turbine/microturbine has several important ramifications to the energy and transportation industry.

The SOFC systems are being developed in the range of 5 kW for automotive applications to several megawatts for power generation applications. The microturbines are being developed from 30 kW to 30 MW and the gas turbines power is in the range of 100–1000 MW. In this paper, a 500-kW SOFC–gas turbine is being analyzed, which can be used as an APU in cruise ships, airplanes, and trains. The same system could be used for distributed power generation applications. If more power is required, more of these systems could be paralleled or the individual systems can be distributed to meet the power demands of the local loads.

A fuel cell/gas turbine hybrid system of 500-kW power is depicted in Fig. 2. The fuel is first reformed to obtain the hydrogen rich reformate and fed to the anode of the SOFC. The ambient air is drawn using a compressor and pressurized to about 300–400 kPa (3–4 atm). The compressed air is heated using the exhaust of the gas turbine with a heat exchanger and fed to the cathode. The cathode exhaust from the SOFC and the unused fuel from the anode are burned in a combustor to increase the temperature of the exhaust to about 1000 °C to meet the requirements of the turbine. The heat and the pressure difference drives the downstream turbine to generate more power without using additional fuel. The turbine exhaust after heating the compressor exit air is also used for heating the fuel that is going into the reformer. The turbine drives the generator and produces a three-phase ac output. This ac power is first converted to the dc power and then combined with the dc output from the fuel cell using the power conditioning system. This dc is converted to the ac output before feeding to the utility.

The gas turbine and the SOFC are tightly coupled in the system. Also, operating with elevated pressure will yield increased power and efficiency for a given cycle. The use of a pressurized SOFC will also lead to optimum integration with the gas turbine. The gas turbine supplies heated compressed air to the SOFC. During normal operating conditions, no additional air or fuel is needed to the gas turbine unit. The reforming process could be endothermic, autothermal, or partial oxidation process. The fuel and air utilization could be varied to give the best system performance within the constraints of stack cooling and heat exchanger metrics. For stationary power generation applications, generally, natural gas is used as the fuel. For trains and ships, diesel fuel is used, and for airplanes, jet fuel is used. The system can use other types of fuels also. The reformer has to be capable of converting these fuels to hydrogen-rich fuel for the fuel cell.

The system has been modeled based on the equations presented in [17]–[19]. The operating parameters for obtaining

TABLE II
TYPICAL PARAMETERS FOR HYBRID SOFC–GAS TURBINE SYSTEM FOR 500-kW OUTPUT

Stack and Reformer	**Value**	**Compressor and Turbine**	**Value**
Stack Power, kW	441	Compressor Inlet Temperature C	15
Stack Area, cm^2	400,000	Compressor Outlet Temperature C	168
Stack Power density, Cm^2	1.1	Compressor Inlet Pressure kPa	101.23
Stack voltage	0.74	Compressor outlet Pressure kPa	323
Stack temperature C	800	Compressor Pressure ratio	3.19
Stack pressure (atm)	3.0	Mass flow through compressor g/s	609
Stack electrical efficiency %	50	Compressor Power kW	93.65
Air utilization %	35	Turbine Inlet Temperature C	1000
Fuel utilization %	85	Turbine Outlet Temperature C	783
Reformer temperature C	677	Turbine Inlet Pressure kPa	288.9
Fuel flow g/s	14.56	Turbine outlet Pressure kPa	105.31
		Turbine Expansion ratio	2.74
		Mass flow through Turbine g/s	623
Stack power + Generator Power kW	**500**	Turbine power kW	161.96
Total system efficiency %	**68.6**	Generator power (available) kW	58

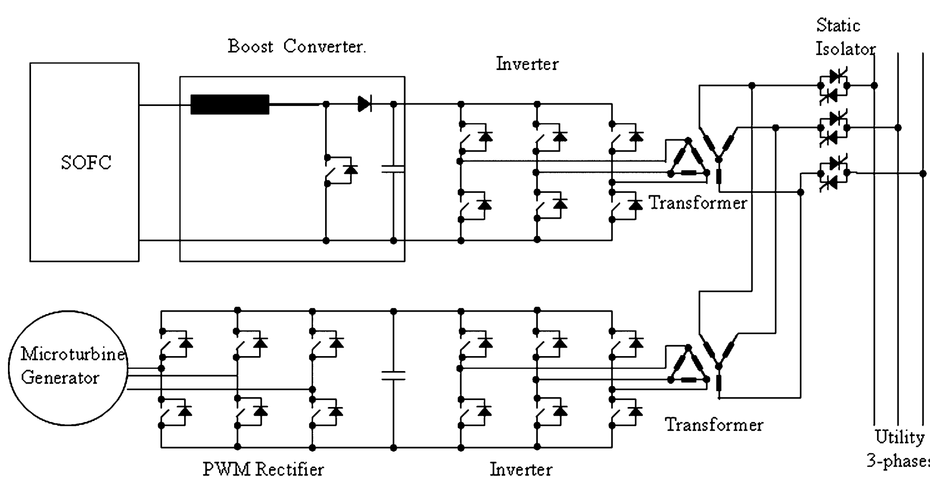

Fig. 3. Electrical system diagram of the hybrid fuel cell/turbine systems.

500-kW power output in a stationary hybrid fuel cell–gas turbine are determined, which are shown in Table II. The mass flow, pressure, and temperature are computed at various points of the system to make sure that the system is balanced, and feasible for practical implementation. The stack power density for a stack area of 400 000 cm^2 is 1.1 W/cm^2, which at present is only in the laboratory demonstration stage. The stack is operated at a pressure ratio of 3.00 to obtain higher efficiency. However, the operating pressure selected is constrained by the operating pressures of the turbine and the compressor. As can be seen from Table II, combining the turbine with the SOFC will result in higher efficiencies of the order of about 68%. If a larger stack size of 500 000 cm^2 is used, the stack power density would be 0.89 W/cm^2 and the combined efficiency would be 71.5% for a 500-kW hybrid power system.

The dc output of the SOFC and the ac output of the turbine–generator system can be combined using several different power conversion configurations. In Fig. 2, the stack output and the generator output are combined on the dc side. In Fig. 3, the fuel-cell voltage is converted to ac using a boost converter and an inverter, and then combined with the three-phase ac output from the generator at the secondary of the three phase transformers. Similar power conversion techniques or variations of these are being used by different fuel-cell system manufacturers [20].

IV. SOFC–TPV SYSTEM

With the improvements in the materials and fabrication technologies, thermoelectric and TPV devices are recently getting more attention to produce electric power [21]–[27]. These devices convert thermal or waste heat energy to electricity. Fig. 4 shows the operating principle of a TPV unit. In a TPV system, the heated emitter produces electromagnetic radiation. A selective filter transmits that part of the radiation with photon energies above the bandgap of the photocells and reflects the lower energy radiation back to the emitter for recuperation. Based on

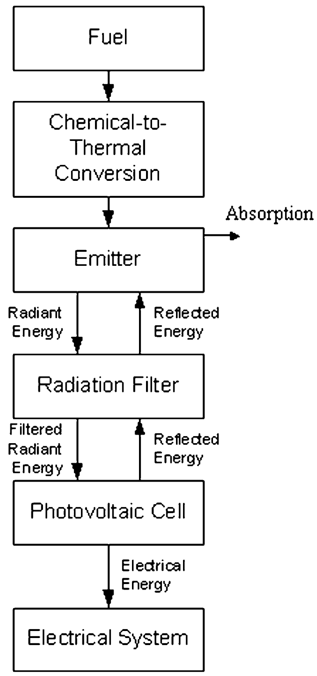

Fig. 4. Operating principle of TPV power generation.

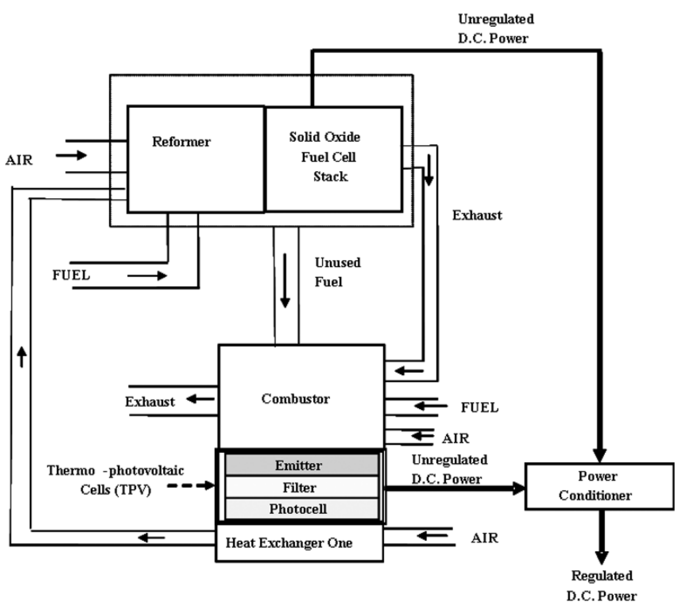

Fig. 5. SOFC and TPV converter hybrid power generation system.

the incident radiation, power is produced by the photovoltaic cells. The TPV device is similar to solar photovoltaic cells except that the source for TPV applications is much closer and has a temperature of around 1500–1800 K rather than 5800 K for the sun. The heat source should have a temperature of about 1200 °C–1500 °C to achieve reasonable conversion efficiency.

The SOFC–TPV hybrid system proposed in this paper is shown in Fig. 5. The hybrid SOFC–thermoelectric device uses the exhaust of the SOFC as a thermal source to produce the required electromagnetic radiation. The exhaust gases coming out of the SOFC are passed through a combustor to increase its temperature to the level required for operation of the TPV. The exhaust gases are heated to the required temperature in the combustor to meet the requirements of the TPV system. This will reduce the fuel requirements for the TPV thermal source. Once the SOFC unit starts operating, the unused fuel from the SOFC unit can be used for further heating the exhaust out of the SOFC unit, and depending on the power required, it is possible to completely cut off the external fuel to the combustor of the TPV unit. The unused fuel from the SOFC itself may be sufficient. Depending on the power rating of the TPV unit, the dc power from the SOFC and the TPV could be combined using a power conditioner system to produce the required ac power. Instead of the TPV, it is possible to use other types of thermoelectric power conversion devices in the fuel-cell hybrid system.

The TPV technology is still in the development stage and is not as efficient as a gas turbine. By using the exhaust of the SOFC as a thermal source, the TPV unit can be used to provide the electric power to the auxiliary loads of the SOFC unit. As the startup time of the TPV is much faster than SOFC, the TPV unit output can provide the electric power to all the critical loads during the SOFC startup process. It marginally contributes to the increase in the combined efficiency of the hybrid system. If the SOFC unit is 45% efficient and the thermoelectric system is 15%, and assuming 65% utilization of the waste heat from the SOFC, the combined efficiency of the hybrid system would be about 50%.

V. PEM Fuel Cell–Wind Power Hybrid System

Recently, there has been a lot of emphasis on the electric power generation using wind energy. Wind turbines are being used not only for grid connection but also as stand-alone power generation systems. Wind power presents some challenges in producing continuous electric power. A significant problem is the intermittent nature of the wind, and the wind power generated depends on wind speed. Combining the wind power generation system with a fuel-cell system would solve some of the problems associated with wind power [28]–[30]. The grid-connected wind–hydrogen system provides off-peak hydrogen production and low-cost electricity. In Fig. 6 is shown a Type–2 hybrid system based on wind power and PEM fuel cell. The wind power is used for generating hydrogen using the electrolysis of water and is stored in cylinders at a certain pressure. This hydrogen is used as the fuel to the fuel-cell stack. The stored hydrogen can also be used to fuel the fuel cell-vehicles. The hybrid system could be configured in several ways.

- The wind power could be used to supply the power to the balance of the plant of the fuel-cell system, particularly during startup of the system, and the excess power could be used to supplement the power from the fuel cell. This is a fuel-cell dominant system and the wind generator supplements the fuel-cell power.
- Hydrogen is generated using electrolysis and stored during the peak power availability from the wind power generation system. The stored hydrogen is used for generating power using the fuel cell during the low output power operation of the wind unit. Electrolyzers can be used to reduce/eliminate surplus wind power generation. Fuel-cell power is generated only during daily peak load

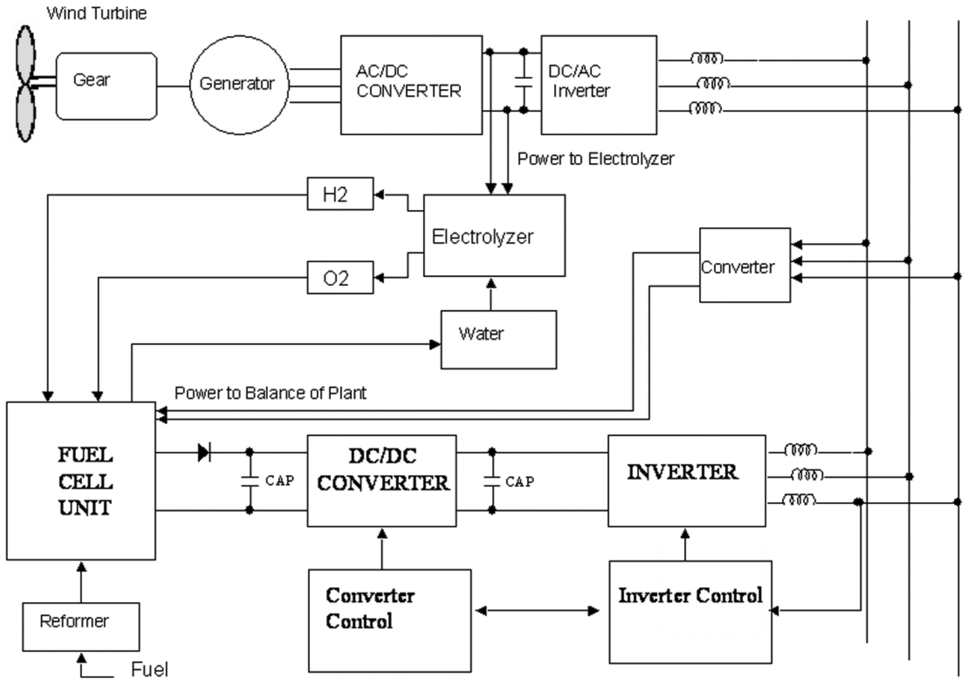

Fig. 6. Wind–fuel cell hybrid power system.

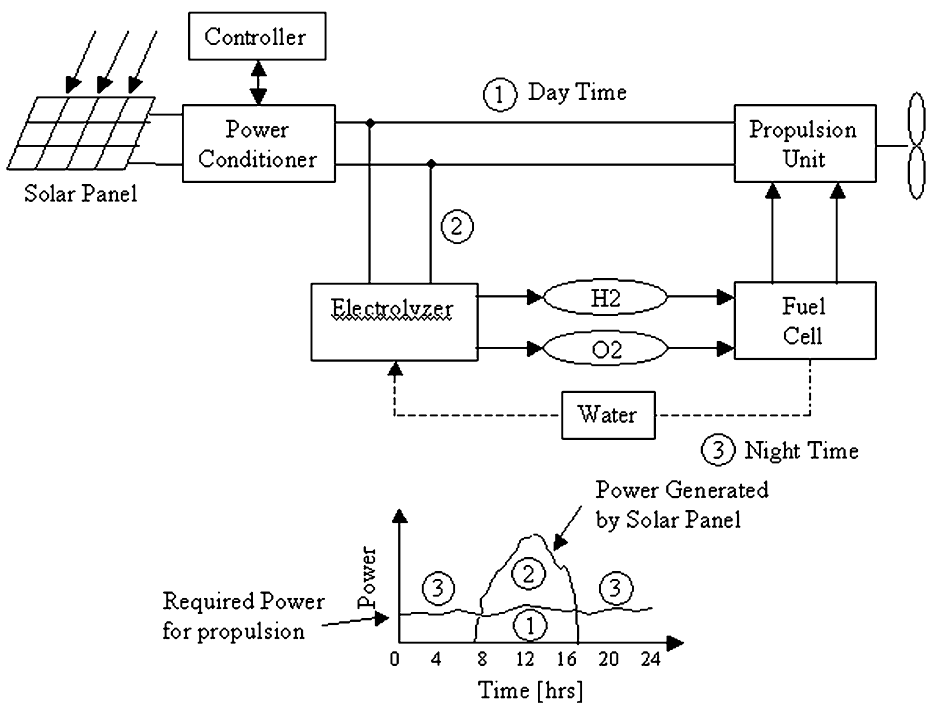

Fig. 7. Hybrid photovoltaic–fuel cell system for a spaceship propulsion application.

period to firm up the wind generation. This is a wind power dominant system and the fuel cell supplements the wind power.

As the hydrogen produced is from the electrolysis of water, it is free from any carbon monoxide. Hence, in this type of application, the PEM fuel cell would be the most applicable choice. The hybrid wind power–fuel-cell system shown in Fig. 6 can be modified to implement any of the above concepts. In addition, depending on the amount of hydrogen stored, the above scheme can be extended to transportation applications by transporting the hydrogen.

VI. Fuel-Cell–Photovoltaic Power Hybrid System

Similar to the wind power, a fuel cell–photovoltaic hybrid system produces hydrogen, stores it, and then converts its energy to electricity for further use. This type of hybrid system is particularly useful in spaceship applications, as shown in Fig. 7

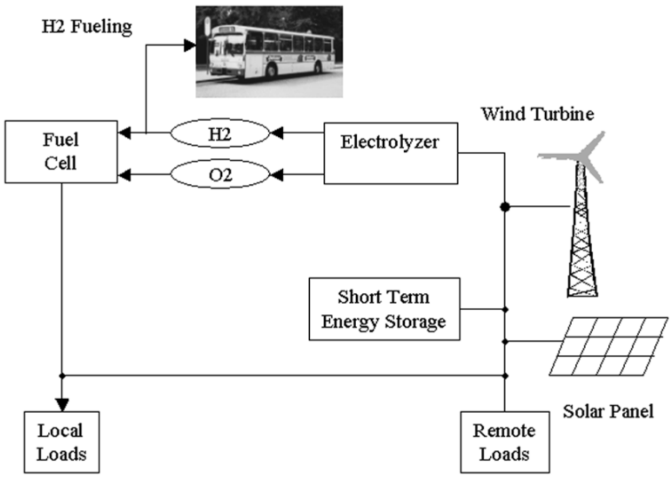

Fig. 8. Hybrid fuel-cell system with wind and solar power.

[31], [32]. During the daytime, the photovoltaic cells convert the solar energy to electricity that is directly used for propelling the spaceship. The excess power is used for generating the hydrogen and oxygen through the electrolysis of water. During the night, the stored H_2 and O_2 are used as the fuel and oxygen supply for the fuel cell to generate electric power to propel the spaceship. Hence, the duration of the power available to the critical loads is maximized. This system can also be used in land-based solar-powered vehicles. Again, for this type of application, considering the operating temperature and availability of pure hydrogen, the PEM fuel cell is the right choice. In this type of system, the operating characteristics of the hybrid system components have to be optimized to provide the power to the load for a maximum amount of time.

The systems shown in Fig. 6 for the wind–fuel-cell hybrid system can be used for a fuel cell–solar power hybrid system in stationary power generation applications. The difference is that solar power is generated only when there is a reasonable amount of availability of sunlight. It is applicable for systems that have enough hydrogen stored to provide the power for the loads during the time of darkness. For larger power generation systems, where the emphasis is on renewable energy, the wind energy could be combined with the solar and fuel-cell power as shown in Fig. 8. This system, combining the fuel-cell power with wind and solar power, would be the ideal situation for reducing the emissions and dependency on fossil fuels [33].

VII. Conclusion

In this paper, the system architectures and the advantages of some of the hybrid fuel-cell systems were discussed. These systems can be used for stationary power generation or for transportation applications. For example, SOFC–microturbine hybrid systems could be used as APUs in airplanes or in trains or ships. The parameters to be optimized depend on the applications. In addition to the systems described in this paper, hybrid power systems could also be configured by combining a fuel cell with other power sources, or by combining two different types of fuel cells, to take advantage of the best characteristics of the individual power sources for a given application.

With the advances in SOFC technology, the SOFC and turbine hybrid systems will be more and more used, not only for stationary power generation, but also for transportation applications. At the same time, with the decreasing costs of generating wind and solar power, more and more electrolysis-based hydrogen-producing stations will be installed in the future. This would increase the use of fuel-cell-based systems for transportation and power generation.

The major hurdle to the commercialization of the technology is economics. The costs of the major components must be significantly reduced. With the advancements in fuel cell, microturbine, wind turbine, and photovoltaic cell technologies, there will be increasing market potential for cogeneration and distribution power generation applications throughout the world.

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