Power-Management Strategies for a Grid-Connected PV-FC Hybrid Systems

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Abstract - This paper presents a method to operate a grid connected hybrid system. The hybrid system composed of a Photovoltaic (PV) array and a Proton exchange membrane fuel cell (PEMFC) is considered. Two operation modes, the unit-power control (UPC) mode and the feeder-flow control (FFC) mode, can be applied to the hybrid system. In the UPC mode, variations of load demand are compensated by the main grid because the hybrid source output is regulated to reference power. Renewable energy is currently widely used. One of these resources is solar energy. The photovoltaic (PV) array normally uses a maximum power point tracking (MPPT) technique to continuously deliver the highest power to the load when there are variations in irradiation and temperature. The disadvantage of PV energy is that the PV output power depends on weather conditions and cell temperature, making it an uncontrollable source. Furthermore, it is not available during the night. In order to overcome these inherent drawbacks, alternative sources, such as PEMFC, should be installed in the hybrid system. By changing the FC output power, the hybrid source output becomes controllable. Therefore, the reference value of the hybrid source output must be determined. In the FFC mode, the feeder flow is regulated to a constant, the extra load demand is picked up by the hybrid source, and, hence, the feeder reference power must be known. He system can maximize the generated power when load is heavy and minimizes the load shedding area. When load is light, the UPC mode is selected and, thus, the hybrid source works more stably. The changes in operating mode only occur when the load demand is at the boundary of mode change; otherwise, the operating mode is either UPC mode or FFC mode. Besides, the variation of hybrid source reference power is eliminated by means of hysteresis. The proposed operating strategy with a flexible operation mode change always operates the PV array at maximum output power and the PEMFC in its high efficiency performance band, thus improving the performance of system operation, enhancing system stability, and decreasing the number of operating mode change s.

INTRODUCTION:

Renewable energy is currently widely used. One of these resources is solar energy. The photovoltaic (PV) array normally uses a maximum power point tracking (MPPT) technique to continuously deliver the highest power to the load when there are variations in irradiation and temperature. The disadvantage of PV energy is that the PV output power depends on weather conditions and cell temperature, making it an uncontrollable source. Furthermore, it is not available during the night. In order to overcome these inherent drawbacks, alternative sources, such as PEMFC, should be installed in the hybrid system. By changing the FC output power, the hybrid source output becomes controllable. However, PEMFC, in its turr $(P_{FC}^{low} \div P_{FC}^{up})$ high efficiency within a specific power range .

The hybrid system can either be connected to the main grid or work autonomously with respect to the grid-connected mode or islanded mode, respectively. In the grid-connected mode, the hybrid source is connected to the main grid at the point of common coupling (PCC) to deliver power to the load. When load demand changes, the power supplied by the main grid and hybrid system must be properly changed.

The power delivered from the main grid and PV array as well as PEMFC must be coordinated to meet load demand. The hybrid source has two control modes: 1) unit-power control (UPC) mode and feeder-flow control (FFC) mode. In the UPC mode, variations of load demand are compensated by the main grid because the hybrid source output is regulated to reference power. P_{MS}^{ref} fore, the reference value of the hybrid source output must be determined. In the FFC mode, the feeder flow is regulated to a constant, the extra load demand is picked up by P_{feeder}^{ref} brid source, and, hence, the feeder reference power must be known.The proposed operating strategy is to coordinate the two control modes and determine the reference values of the UPC mode and FFC mode so that all constraints are satisfied. This operating strategy will minimize the number of operating mode changes, improve performance of the system operation, and enhance system stability.

DISTRIBUTED GENERATION:

Distributed eneration, also called on-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy or distributed energy generates electricity from many small energy sources. Currently, industrial countries generate most of their electricity in large centralized facilities, such as fossil fuel (coal, gas powered) nuclear or hydropower plants. These plants have excellent economies of scale, but usually transmit electricity long distances and negatively affect the environment.

Most plants are built this way due to a number of economic, health & safety, logistical. For example, coal power plants are built away from cities to prevent their heavy air pollution from affecting the populace. In addition, such plants are often built near collieries to minimize the cost of transporting coal. Hydroelectric plants are by their nature limited to operating at sites with sufficient water flow. Most power plants are often considered to be too far away for their waste heat to be used for heating buildings.Distributed generation is another approach. It reduces the amount of energy lost in transmitting electricity because the electricity is generated very near where it is used, perhaps even in the same building. This also reduces the size and number of power lines that must be constructed. Typical distributed power sources in a Feed-in Tariff (FIT) scheme have low maintenance, low pollution and high efficiencies. In the past, these traits required dedicated operating engineers and large complex plants to reduce pollution. However, modern embedded systems can provide these traits with automated operation and renewables, such as sunlight, wind and geothermal. This reduces the size of power plant that can show a profit.

DISTRIBUTED ENERGY RESOURCE

Distributed energy resource (DER) systems are small-scale power generation technologies (typically in the range of 3 kW to 10,000 kW) used to provide an alternative to or an enhancement of the traditional electric power system. The usual problems with distributed generators are their high costs.One popular source is solar panels on the roofs of buildings. The production cost is $0.99 to 2.00/W (2007) plus installation and supporting equipment unless the installation is Do it yourself (DIY) bringing the cost to $6.50 to 7.50 (2007). This is comparable to coal power plant costs of $0.582 to 0.906/W (1979), adjusting for inflation. Nuclear power is higher at $2.2 to $6.00/W (2007). Some solar cells ("thin-film" type) also have waste disposal issues, since "thin-film" type solar cells often contain heavy-metal electronic wastes, such as Cadmium telluride (CdTe) and Copper indium gallium selenide (CuInGaSe), and need to be recycled. As opposed to silicon semi-conductor type solar cells which is made from quartz. The plus side is that unlike coal and nuclear, there are no fuel costs, pollution, mining safety or operating safety issues. Solar also has a low duty cycle, producing peak power at local noon each day. Average duty cycle is typically 20%.

Another source is small wind turbines. These have low maintenance, and low pollution. Construction costs are higher ($0.80/W, 2007) per watt than large power plants, except in very windy areas. Wind towers and generators have substantial insurable liabilities caused by high winds, but good operating safety. In some areas of the US there may also be Property Tax costs involved with wind turbines that are not offset by incentives or accelerated depreciation. Wind also tends to be complementary to solar; on days there is no sun there tends to be wind and vice versa. Many distributed generation sites combine wind power and solar power such as Slippery Rock University, which can be monitored online.

Distributed cogeneration sources use natural gas-fired micro turbines or reciprocating engines to turn generators. The hot exhaust is then used for space or water heating, or to drive an absorptive chiller for air-conditioning. The clean fuel has only low pollution. Designs currently have uneven reliability, with some makes having excellent maintenance costs, and others being unacceptable.Co-generators are also more expensive per watt than central generators. They find favor because most buildings already burn fuels, and the cogeneration can extract more value from the fuel. Some larger installations utilize combined cycle generation. Usually this consists of a gas turbine whose exhaust boils water for a steam turbine in a Rankin cycle. The condenser of the steam cycle provides the heat for space heating or an absorptive chiller. Combined cycle plants with cogeneration have the highest known thermal efficiencies, often exceeding 85%.In countries with high pressure gas distribution, small turbines can be used to bring the gas pressure to domestic levels whilst extracting useful energy. If the UK were to implement this countrywide an additional 2-4 GWe would become available. (Note that the energy is already being generated elsewhere to provide the high initial gas pressure - this method simply distributes the energy via a different route.)Future generations of electric vehicles will have the ability to deliver power from the battery into the grid when needed. This could also be an important distributed generation resource. Recently interest in Distributed Energy Systems (DES) is increasing, particularly onsite generation. This interest is because larger power plants are economically unfeasible in many regions due to increasing system and fuel costs, and more strict environmental regulations. In addition, recent technological advances in small generators, Power Electronics, and energy storage devices have provided a new opportunity for distributed energy resources at the distribution level, and especially, the incentive laws to utilize renewable energies has also encouraged a more decentralized approach to power delivery.There are many generation sources for DES: conventional technologies (diesel or natural gas engines), emerging technologies (micro turbines or fuel cells or energy storage devices), and renewable technologies (small wind turbines or solar/photovoltaic's or small hydro turbines). These DES are used for applications to a standalone, a standby, a grid-interconnected, a cogeneration, peak shavings, etc. and have many advantages such as environmental-friendly and modular electric generation, increased reliability, high power quality, uninterruptible service, cost savings, on-site generation, expandability, etc. So many utility companies are trying to construct small distribution stations combined with several DES available at the regions, instead of large power plants. Basically, these technologies are based on notably advanced Power Electronics because all DES require Power Converters, interconnection techniques, and electronic control units. That is, all power generated by DES is generated as DC Power, and then all the power fed to the DC distribution bus is again converted into an AC power with fixed magnitude and frequency by control units using Digital Signal Processor (DSP). So improved power electronic technologies that permit grid interconnection of asynchronous generation sources are definitely required to support distributed generation resources

The research works in the recent papers about DES focus on being utilized directly to a standalone AC system or fed back to the utility mains. That is, when in normal operation or main failures, DES directly supply loads with power (standalone mode or standby mode), while, when DES have surplus power or need more power, this system operates in parallel mode to the mains. Therefore, in order to permit to connect more generators on the network in good conditions, a good technique about interconnection with the grid and voltage regulations should overcome the problems due to parallel operation of Power Converter for applications to DES.

DISTRIBUTED ENERGY SYSTEMS

Today, new advances in technology and new directions in electricity regulation encourage a significant increase of distributed generation resources around the world. As shown in Fig. the currently competitive small generation units and the incentive laws to use renewable energies force electric utility companies to construct an increasing number of distributed generation units on its distribution network, instead of large central power plants. Moreover, DES can offer improved service reliability, better economics and a reduced dependence on the local utility. Distributed Generation Systems have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had stand-by diesel generation as an emergency power source for use only during outages. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anything except for an emergency basis.

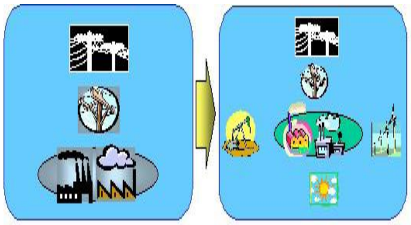


Fig. A large central power plant and distributed energy systems

Meanwhile, recently, the use of Distributed Energy Systems under the 500 kW level is rapidly increasing due to recent technology improvements in small generators, power electronics, and energy storage devices. Efficient clean fossil fuels technologies such as micro-turbines and fuel cells, and environmentally friendly renewable energy technologies such as solar/photo voltaic, small wind and hydro are increasingly used for new distributed generation systems. These DES are applied to a standalone, a standby, a grid-interconnected, a cogeneration, peak shavings, etc. and have a lot of benefits such as environmental-friendly and modular electric generation, increased reliability, high power quality, uninterruptible service, cost savings, on-site generation, Expandability, etc. The major Distributed Generation technologies that will be discussed in this section are as follows: micro-turbines, fuel cells, solar/photovoltaic systems, and energy storage devices. Micro-turbines, especially the small gas fired micro turbines in the 25-100 kW that can be mass-produced at low cost have been more attractive due to the competitive price of natural gas, low installation and maintenance costs. It takes very clever engineering and use of innovative design (e.g. air bearing, recuperation) to achieve reasonable efficiency and costs in machines of lower output, and a big advantage of these systems is small because these mainly use high-speed turbines (50,000-90,000 RPM) with air foil bearings. Therefore, micro turbines hold the most promise of any of the DES technologies today. 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 produced from natural gas, or liquid fuels such as alcohols, or gasoline. Each unit ranges in size from 3 – 250 kW or larger MW size. Even if they offer high efficiency and low emissions, today's costs are high. 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 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.Mixed micro-turbine and fuel cell systems will also be available as a distributed generation source. Recently, a solid oxide fuel cell has been combined with a gas micro-turbine creating a combined cycle power plant. It has expected electrical efficiency of greater than 70 %, and the expected power levels range from 250 kW to 2.5 MW. Solar/photovoltaic systems may be used in a variety of sizes, but the installation of large numbers of photovoltaic systems is undesirable due to high land costs and in many geographic areas with poor intensity and reliability of sunlight. In general, almost one acre of land would be needed to provide 150 kW of electricity, so solar/photovoltaic systems will continue to have limited applications in the future. Energy storage devices such as ultra capacitors, batteries, and flywheels are one of the most critical technologies for DES. In general, the electrochemical capacitor has high power density as well as good energy density. In particular, ultra capacitors have several benefits such as high pulse power capacity, long lifetime, high power density, low ESR, and very thin and tight. In contrast, batteries have higher energy density, but lower power density and short lifetime relative to ultra-capacitor. So hybrid Power System, a combination of ultra-capacitor and battery, is strongly recommended to satisfy several requirements and to optimize system performance. Recently storage systems are much more efficient, cheaper, and longer than five years ago. In particular, flywheel systems can generate 700 kW for 5 seconds, while 28-cell ultra capacitors can provide up to 12.5 kW for a few seconds. In the past, the electric utility industry did not offer various options that were suited for a wide range of consumer needs, and most utilities offered at best two or three combinations of reliability-price. However, the types of modern DES give commercial electric consumers various options in a wider range of reliability-price combinations. For these reasons, DES will be very likely to thrive in the next 20 years, and especially, distributed generation technologies will have a much greater market potential in areas with high electricity costs and low reliability such as in developing countries

PROBLEM STATEMENTS

DES technologies have very different issues compared with traditional centralized power sources. For example, they are applied to the mains or the loads with voltage of 480 volts or less; and require power converters and different strategies of control and dispatch. All of these energy technologies provide a DC output which requires power electronic interfaces with the distribution power networks and its loads. In most cases the conversion is performed by using a voltage source inverter (VSI) with a possibility of pulse width modulation (PWM) that provides fast regulation for voltage magnitude.

Power electronic interfaces introduce new control issues, but at the same time, new possibilities. For example, a system which consists of micro-generators and storage devices could be designed to operate in both an autonomous mode and connected to the power grid. One large class of problems is related to the fact that the power sources such as microturbines and fuel cell have slow response and their inertia is much less. It must be remembered that the current power systems have storage in generators' inertia, and this may result in a slight reduction in system frequency. As these generators become more compact, the need to link them to lower network voltage is significantly increasing.

However, without any medium voltage networks adaptation, this fast expansion can affect the quality of supply as well as the public and equipment safety because distribution networks have not been designed to connect a significant amount of generation. Therefore, a new voltage control system to facilitate the connection of distributed generation resources to distribution networks should be developed.

In many cases there are also major technical barriers to operating independently in a standalone AC system, or to connecting small generation systems to the electrical distribution network with lower voltage, and the recent research issues includes:

1. Control strategy to facilitate the connection of distributed generation resources to distribution networks.
2. Efficient battery control.
3. Inverter control based on only local information.

4. Synchronization with the utility mains.
5. Compensation of the reactive power and higher harmonic components.
6. Power Factor Correction.
7. System protection.
8. Load sharing.
9. Reliability of communication.
10. Requirements of the customer.

DES offers significant research and engineering challenges in solving these problems. Moreover, the electrical and economic relationships between customers and the distribution utility and among customers may take forms quite distinct from those we know today. For example, rather than devices being individually interconnected in parallel with the grid, they may be grouped with loads in a semi-autonomous neighborhood that could be termed a micro grid is a cluster of small sources, storage systems, and loads which presents itself to the grid as a legitimate single entity. Hence, future research work will focus on solving the above issues so that DES with more advantages compared with tradition large power plants can thrive in electric power industry.

MODELING AND CONTROL OF INVERTER INTERFACED DG UNITS

Basically each DG unit may have DC type or rectified generation unit (Fuel cell, solar cell, wind turbine, micro turbine…), storage devices, DC-DC converter, DC-AC inverter, filter, and transformer for connecting to loads or utility in order to exchange power. Model and dynamic of each of this part may have influence in system operation. But here for simplification it is considered that DC side of the units has sufficient storage and considered as a constant DC source. Hence only DC-AC inverter modeling and control investigated in this paper.A circuit model of a three-phase DC to AC inverter with LC output filter is further described in Figure As shown in the figure, the system consists of a DC voltage source (Vdc), a three- phase PWM inverter, an output filter (Lf and C with considering parasitic resistance of filter- Rf). Sometimes a transformer may be used for stepping up the output voltage and hence Lf can be transformer inductance.

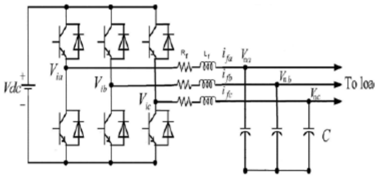


Figure PWM inverter diagram

There are two ways for controlling an inverter in a distributed generation system

A. PQ Inverter Control

This type of control is adopted when the DG unit system is connected to an external grid or to an island of loads and more generators. In this situation, the variables controlled by the inverter are the active and reactive power injected into the grid, which have to follow the set points Pref and Qref, respectively. These set points can be chosen by the customer or by a central controller. The PQ control of an inverter can be performed using a current control technique in qd reference frame which the inverter current is controlled in amplitude and phase to meet the desired set-points of active and reactive power.With the aim of Park transform and equations between inverter input and output, the inverter controller block diagram for supplying reference value of Pref and Qref is as figures. For the current controller, two Proportional-Integral (PI) regulators have been chosen in order to meet the requirements of stability of the system and to make the steady state error be zero. With this control scheme, it is possible to control the inverter in such way that injects reference value of Pref, Qref into other part of stand-alone network. When the output voltage is needed to be regulated, the PV control scheme that is similar to PQ mode with feedback of voltage used to adjust Qref.

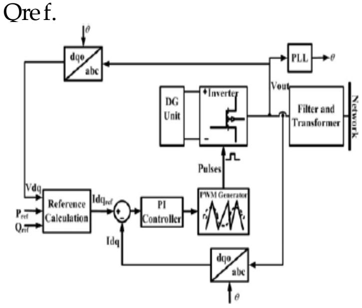


Figure : PQ control scheme of inverter

B. Vf Inverter Control

This controller has to act on the inverter whenever the system is in stand-alone mode of operation. In fact in this case it must regulate the voltage value at a reference bus bar and the frequency of the whole grid. A regulators work in order to keep the measured voltages upon the set points. Moreover the frequency is imposed through the modulating signals of the inverter PWM control by mean of an oscillator. A simple PI controller can regulate bus voltage in reference value with getting feedback of real bus voltage.

Figure outlines this control strategy. In this case it is obvious that the DG unit should have storage device in order to regulate the power and voltage.

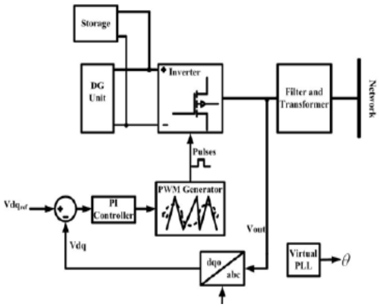


Figure: Vf control scheme of inverter

III. FUEL CELL:

Introduction:

A fuel cell is an electrochemical cell that converts a source fuel into an electrical current. It generates electricity inside a cell through reactions between a fuel and an oxidant, triggered in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate continuously as long as the necessary reactant and oxidant flows are maintained.

Fuel cells are different from conventional electrochemical cell batteries in that they consume reactant from an external source, which must be replenished[1] – a thermodynamically open system. By contrast, batteries store electrical energy chemically and hence represent a thermodynamically closed system.

Many combinations of fuels and oxidants are possible. A hydrogen fuel cell uses hydrogen as its fuel and oxygen (usually from air) as its oxidant. Other fuels include hydrocarbons and alcohols. Other oxidants include chlorine and chlorine dioxide

Fuel cells come in many varieties; however, they all work in the same general manner. They are made up of three segments which are sandwiched together: the anode, the electrolyte, and the cathode. Two chemical reactions occur at the interfaces of the three different segments. The net result of the two reactions is that fuel is consumed, water or carbon dioxide is created, and an electrical current is created, which can be used to power electrical devices, normally referred to as the load.

At the anode a catalyst oxidizes the fuel, usually hydrogen, turning the fuel into a positively charged ion and a negatively charged electron. The electrolyte is a substance specifically designed so ions can pass through it, but the electrons cannot. The freed electrons travel through a wire creating the electrical current. The ions travel through the electrolyte to the cathode. Once reaching the cathode, the ions are reunited with the electrons and the two react with a third chemical, usually oxygen, to create water or carbon dioxide.

DESIGN FEATURES IN A FUEL CELL ARE:

The electrolyte substance. The electrolyte substance usually defines the type of fuel cell. The fuel that is used. The most common fuel is hydrogen.The anode catalyst, which breaks down the fuel into electrons and ions. The anode catalyst is usually made up of very fine platinum powder. The cathode catalyst, which turns the ions into the waste chemicals like water or carbon dioxide. The cathode catalyst is often made up of nickel. A typical fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. Voltage decreases as current increases, due to several factors:Activation loss ,Ohmic loss (voltage drop due to resistance of the cell components and interconnects)

Mass transport loss (depletion of reactants at catalyst sites under high loads, causing rapid loss of voltage). To deliver the desired amount of energy, the fuel cells can be combined in series and parallel circuits, where series yields higher voltage, and parallel allows a higher current to be supplied. Such a design is called a fuel cell stack. The cell surface area can be increased, to allow stronger current from each cell.

Types of fuel cells:

Proton exchange fuel cells:In the archetypal hydrogen–oxygen proton exchange membrane fuel cell (PEMFC) design, a proton-conducting polymer membrane, (the electrolyte), separates the anode and cathode sides. This was called a "solid polymer electrolyte fuel cell" (SPEFC) in the early 1970s, before the proton exchange mechanism was well-understood. (Notice that "polymer electrolyte membrane" and "proton exchange mechanism" result in the same acronym.)On the anode side, hydrogen diffuses to the anode catalyst where it later dissociates into protons and electrons. These protons often react with oxidants causing them to become what is commonly referred to as multi-facilitated proton membranes. The protons are conducted through the membrane to the cathode, but the electrons are forced to travel in an external circuit (supplying power) because the membrane is electrically insulating. On the cathode catalyst, oxygen molecules react with the electrons (which have traveled through the external circuit) and protons to form water.The materials used in fuel cells differ by type. In a typical membrane electrode assembly (MEA), the electrode–bipolar plates are usually made of metal, nickel or carbon nano tubes, and are coated with a catalyst (like platinum, nano iron powders or palladium) for higher efficiency. Carbon paper separates them from the electrolyte. The electrolyte could be ceramic or a membrane.Proton exchange membrane fuel cell design issues:Costs. In 2002, typical fuel cell systems cost US$1000 per kilowatt of electric power output. In 2009, the Department of Energy reported that 80-kW automotive fuel cell system costs in volume production (projected to 500,000 units per year) are $61 per kilowatt. The goal is $35 per kilowatt. In 2008 UTC Power has 400 kW stationary fuel cells for $1,000,000 per 400 kW installed costs. The goal is to reduce the cost in order to compete with current market technologies including gasoline internal combustion engines. Many companies are working on techniques to reduce cost in a variety of ways including reducing the amount of platinum needed in each individual cell. Ballard Power Systems have experiments with a catalyst enhanced with carbon silk which allows a 30% reduction (1 mg/cm² to 0.7 mg/cm²) in platinum usage without reduction in performance. Monash University, Melbourne uses PEDOT as a cathode. The production costs of the PEM (proton exchange membrane). The Nafion membrane currently costs $566/m². In 2005 Ballard Power Systems announced that its fuel cells will use Sholapur, a porous polyethylene film patented by DSM.

Water and air management (in PEMFCs). In this type of fuel cell, the membrane must be hydrated, requiring water to be evaporated at precisely the same rate that it is produced. If water is evaporated too quickly, the membrane dries, resistance across it increases, and eventually it will crack, creating a gas "short circuit" where hydrogen and oxygen combine directly, generating heat that will damage the fuel cell. If the water is evaporated too slowly, the electrodes will flood, preventing the reactants from reaching the catalyst and stopping the reaction. Methods to manage water in cells are being developed like electro osmotic pumps focusing on flow control. Just as in a combustion engine, a steady ratio between the reactant and oxygen is necessary to keep the fuel cell operating efficiently.

Temperature management. The same temperature must be maintained throughout the cell in order to prevent destruction of the cell through thermal loading. This is particularly challenging as the $2H_2 + O_2 \rightarrow 2H_2O$ reaction is highly exothermic, so a large quantity of heat is generated within the fuel cell.

Durability, service life, and special requirements for some type of cells. Stationary fuel cell applications typically require more than 40,000 hours of reliable operation at a temperature of -35 °C to 40 °C (-31 °F to 104 °F), while automotive fuel cells require a 5,000 hour lifespan (the equivalent of 150,000 miles) under extreme temperatures. Current service life is 7,300 hours under cycling conditions.[11] Automotive engines must also be able to start reliably at -30 °C (-22 °F) and have a high power to volume ratio (typically 2.5 kW per liter).

Limited carbon monoxide tolerance of the cathode.

High temperature fuel cells:

A solid oxide fuel cell:

A solid oxide fuel cell (SOFC) is extremely advantageous “because of a possibility of using a wide variety of fuel” [. Unlike most other fuel cells which only use hydrogen, SOFCs can run on hydrogen, butane, methanol, and other petroleum products. The different fuels each have their own chemistry.

For methanol fuel cells, on the anode side, a catalyst breaks methanol and water down to form carbon dioxide, hydrogen ions, and free electrons. The hydrogen ions move across the electrolyte to the cathode side, where they react with oxygen to create water. A load connected externally between the anode and cathode completes the electrical circuit. Below are the chemical equations for the reaction:

Anode Reaction: $CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$

Cathode Reaction: $3/2\, O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$

Overall Reaction: $CH_3OH + 3/2\, O_2 \rightarrow CO_2 + 2H_2O$ + electrical energy.

At the anode SOFCs can use nickel or other catalysts to break apart the methanol and create hydrogen ions and CO_2. A solid called yttrium stabilized zirconia (YSZ) is used as the electrolyte. Like all fuel cell electrolytes YSZ is conductive to ions, allowing them to pass from the anode to cathode, but is non-conductive to electrons. YSZ is a durable solid and is advantageous in large industrial systems. Although YSZ is a good ion conductor, it only works at very high temperatures.

The standard operating temperature is about 950°C. Running the fuel cell at such a high temperature easily breaks down the methane and oxygen into ions. A major disadvantage of the SOFC, as a result of the high heat, is that it “places considerable constraints on the materials which can be used for interconnections”. Another disadvantage of running the cell at such a high temperature is that other unwanted reactions may occur inside the fuel cell. It is common for carbon dust, graphite, to build up on the anode, preventing the fuel from reaching the catalyst. Much research is currently being done to find alternatives to YSZ that will carry ions at a lower temperature.

MCFC:

Molten-carbonate fuel cells (MCFCs) are high-temperature fuel cells, that operate at temperatures of 600°C and above.Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte (BASE). Since they operate at extremely high temperatures of 650°C (roughly 1,200°F) and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs.Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells (PAFCs). Molten carbonate fuel cells can reach efficiencies approaching 60 percent, considerably higher than the 37-42 percent efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85 percent.Unlike alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which MCFCs operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.Molten carbonate fuel cells are not prone to poisoning by carbon monoxide or carbon dioxide —they can even use carbon oxides as fuel— making them more attractive for fueling with gases made from coal. Because they are more resistant to impurities than other fuel cell types, scientists believe that they could even be capable of internal reforming of coal, assuming they can be made resistant to impurities such as sulfur and particulates that result from converting coal, a dirtier fossil fuel source than many others, into hydrogen.The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that increase cell life without decreasing performance.

Fuel cell efficiency:

The efficiency of a fuel cell is dependent on the amount of power drawn from it. Drawing more power means drawing more current, this increases the losses in the fuel cell. As a general rule, the more power (current) drawn, the lower the efficiency. Most losses manifest themselves as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage. For this reason, it is common to show graphs of voltage versus current (so-called polarization curves) for fuel cells. A typical cell running at 0.7 V has an efficiency of about 50%, meaning that 50% of the energy content of the hydrogen is converted into electrical energy; the remaining 50% will be converted into heat. (Depending on the fuel cell system design, some fuel might leave the system unreacted, constituting an additional loss.).For a hydrogen cell operating at standard conditions with no reactant leaks, the efficiency is equal to the cell voltage divided by 1.48 V, based on the enthalpy, or heating value, of the reaction. For the same cell, the second law efficiency is equal to cell voltage divided by 1.23 V. (This voltage varies with fuel used, and quality and temperature of the cell.) The difference between these numbers represents the difference between the reaction's enthalpy and Gibbs free energy. This difference always appears as heat, along with any losses in electrical conversion efficiency.Fuel cells do not operate on a thermal cycle. As such, they are not constrained, as combustion engines are, in the same way by thermodynamic limits, such as Carnot cycle efficiency. At times this is misrepresented by saying that fuel cells are exempt from the laws of thermodynamics, because most people think of thermodynamics in terms of combustion processes (enthalpy of formation). The laws of thermodynamics also hold for chemical processes (Gibbs free energy) like fuel cells, but the maximum theoretical efficiency is higher (83% efficient at 298K in the case of hydrogen/oxygen reaction) than the Otto cycle thermal efficiency (60% for compression ratio of 10 and specific heat ratio of 1.4).

Comparing limits imposed by thermodynamics is not a good predictor of practically achievable efficiencies. Also, if propulsion is the goal, electrical output of the fuel cell has to still be converted into mechanical power with another efficiency drop. In reference to the exemption claim, the correct claim is that the "limitations imposed by the second law of thermodynamics on the operation of fuel cells are much less severe than the limitations imposed on conventional energy conversion systems".[23] Consequently, they can have very high efficiencies in converting chemical energy to electrical energy, especially when they are operated at low power density, and using pure hydrogen and oxygen as reactants.It should be underlined that fuel cell (especially high temperature) can be used as a heat source in conventional heat engine (gas turbine system). In this case the ultra high efficiency is predicted (above 70%).

In practice:

For a fuel cell operating on air, losses due to the air supply system must also be taken into account. This refers to the pressurization of the air and dehumidifying it. This reduces the efficiency significantly and brings it near to that of a compression ignition engine. Furthermore, fuel cell efficiency decreases as load increases.The tank-to-wheel efficiency of a fuel cell vehicle is greater than 45% at low loads and shows average values of about 36% when a driving cycle like the NEDC (New European Driving Cycle) is used as test procedure. The comparable NEDC value for a Diesel vehicle is 22%. In 2008 Honda released a fuel cell electric vehicle (the Honda FCX Clarity) with fuel stack claiming a 60% tank-to-wheel efficiency. It is also important to take losses due to fuel production, transportation, and storage into account. Fuel cell vehicles running on compressed hydrogen may have a power-plant-to-wheel efficiency of 22% if the hydrogen is stored as high-pressure gas, and 17% if it is stored as liquid hydrogen.[29] In addition to the production losses, over 70% of US' electricity used for hydrogen production comes from thermal power, which only has an efficiency of 33% to 48%, resulting in a net increase in carbon dioxide production by using hydrogen in vehicles[Fuel cells cannot store energy like a battery, but in some applications, such as stand-alone power plants based on discontinuous sources such as solar or wind power, they are combined with electrolyzes and storage systems to form an energy storage system.The overall efficiency (electricity to hydrogen and back to electricity) of such plants (known as round-trip efficiency) is between 30 and 50%, depending on conditions. While a much cheaper lead-acid battery might return about 90%, the electrolyze/fuel cell system can store indefinite quantities of hydrogen, and is therefore better suited for long-term storage.Solid-oxide fuel cells produce exothermic heat from the recombination of the oxygen and hydrogen. The ceramic can run as hot as 800 degrees Celsius. This heat can be captured and used to heat water in a micro combined heat and power (m-CHP) application. When the heat is captured, total efficiency can reach 80-90% at the unit, but does not consider production and distribution losses. CHP units are being developed today for the European home market.Stationary fuel cell applications (or stationary fuel cell power systems) are stationary that are either connected to the electric grid (distributed generation) to provide supplemental power and as emergency power system for critical areas, or installed as a grid-independent generator for on-site service.
Codes and standards Stationary fuel cell applications is a classification in FC Hydrogen codes and standards and fuel cell codes and standards. The other main standards are **Portable fuel cell applications and Fuel cell vehicle.**

Fuel cell gas appliances up to 70 kW .Installation permitting guidance for hydrogen and fuel cells stationary applications
Standard for the installation of stationary fuel cell power systems

Emergency power systems:

Emergency power systems are a type fuel cell system, which may include lighting, generators and other apparatus, to provide backup resources in a crisis or when regular systems fail. They find uses in a wide variety of settings from residential homes to hospitals, scientific laboratories, data centers, telecommunication equipment and modern naval ships.

Uninterrupted power supply:

An uninterrupted power supply (UPS) provides emergency power and, depending on the topology, provide line regulation as well to connected equipment by supplying power from a separate source when utility power is not available. It differs from an auxiliary power supply or standby generator, which does not provide instant protection from a momentary power interruption.

Cogeneration

Cogeneration can be used when the fuel cell is sited near the point of use, its waste heat can be captured for beneficial purposes. Micro combined heat and power (MicroCHP) is usually less than 5 kWe for a home fuel cell or small business.

POWER:

Fuel cells are very useful as power sources in remote locations, such as spacecraft, remote weather stations, large parks, rural locations, and in certain military applications. A fuel cell system running on hydrogen can be compact and lightweight, and have no major moving parts. Because fuel cells have no moving parts and do not involve combustion, in ideal conditions they can achieve up to 99.9999% reliability. This equates to around one minute of down time in a two year period.Since electrolyses systems do not store fuel in themselves, but rather rely on external storage units, they can be successfully applied in large-scale energy storage, rural areas being one example. In this application, batteries would have to be largely oversized to meet the storage demand, but fuel cells only need a larger storage unit (typically cheaper than an electrochemical device).

Cogeneration:

Micro combined heat and power (MicroCHP) systems such as home fuel cells and cogeneration for office buildings and factories are in the mass production phase. The system generates constant electric power (selling excess power back to the grid when it is not consumed), and at the same time produces hot air and water from the waste heat. MicroCHP is usually less than 5 kWe for a home fuel cell or small business.
A lower fuel-to-electricity conversion efficiency is tolerated (typically 15-20%), because most of the energy not converted into electricity is utilized as heat. Some heat is lost with the exhaust gas just as in a normal furnace, so the combined heat and power efficiency is still lower than 100%, typically around 80%. In terms of energy however, the process is inefficient, and one could do better by maximizing the electricity generated and then using the electricity to drive a heat pump. Phosphoric-acid fuel cells (PAFC) comprise the largest segment of existing CHP products worldwide and can provide combined efficiencies close to 90% (35-50% electric + remainder

as thermal) Molten-carbonate fuel cells have also been installed in these applications, and solid-oxide fuel cell prototypes exist.

Other applications:

- Providing power for base stations or cell sites
- Off-grid power supply
- Distributed generation
- Fork Lifts

Emergency power systems are a type of fuel cell system, which may include lighting, generators and other apparatus, to provide backup resources in a crisis or when regular systems fail. They find uses in a wide variety of settings from residential homes to hospitals, scientific laboratories, data centers, telecommunication equipment and modern naval ships.

An uninterrupted power supply (UPS) provides emergency power and, depending on the topology, provide line regulation as well to connected equipment by supplying power from a separate source when utility power is not available. Unlike a standby generator, it can provide instant protection from a momentary power interruption.

- Base load power plants
- Electric and hybrid vehicles.

Notebook computers for applications where AC charging may not be available for weeks at a time.

Smartphone with high power consumption due to large displays and additional features like GPS might be equipped with micro fuel cells.

- Small heating appliances.

Fuel cells are a technology that both the public and private sectors are increasingly turning to for both primary and back-up power needs. Although the understanding of the chemistry of fuel cells goes back more than a century, they are very much a 21st century technology. The basic design and electrochemical principle behind fuel cells is straightforward. A fuel cell stack requires only hydrogen (or a similar energy carrier), oxygen, and an electrolytic solution.

Hydrogen and ambient air flow into the fuel cell, which contains an anode and a cathode. At the anode, the hydrogen separates into a proton and an electron. The proton migrates to the cathode, where it reacts with the oxygen to form water. The electrons, which cannot pass through the membrane, flow from the cell to provide useful electrical power. Fuel cells are quiet, have no moving parts, and produce no particulate emissions. They are virtually maintenance free and can be both tested and operated remotely. Because they are modular, they can be configured for any size power needs, from a few kilowatts for a remote telecommunications tower to megawatt-scale for hospitals and airports. Hydrogen is safely stored on-site or produced within the fuel cell itself.

SOLID OXIDE FUEL CELLS:

Solid oxide fuel cells (SOFCs) offer a clean, low-pollution technology to electrochemically generate electricity at high efficiencies; since their efficiencies are not limited the way conventional heat engine's is. These fuel cells provide many advantages over traditional energy conversion systems including high efficiency, reliability, modularity, fuel adaptability, and very low levels of polluting emissions. Quiet, vibration-free operation of SOFCs also eliminates noise usually associated with conventional power generation systems.

Up until about six years ago, SOFCs were being developed for operation primarily in the temperature range of 900 to 1000°C (1692 to 1832°F); in addition to the capability of internally reforming hydrocarbon fuels (for example, natural gas), such high temperature SOFCs provide high quality exhaust heat for cogeneration, and when pressurized, can be integrated with a gas turbine to further increase the overall efficiency of the power system. However, reduction of the SOFC operating temperature by 200°C (392°F) or more allows use of a broader set of materials, is less demanding on the seals and the balance-of-plant components, simplifies thermal management, aids in faster start up and cool down, and results in less degradation of cell and stack components. Because of these advantages, activity in the development of SOFCs capable of operating in the temperature range of 650 to 800°C (1202 to 1472°F) has increased dramatically in the last few years. However, at lower temperatures, electrolyte conductivity and electrode kinetics decrease significantly; to overcome these drawbacks, alternative cell materials and designs are being extensively investigated.

An SOFC essentially consists of two porous electrodes separated by a dense, oxide ion conducting electrolyte. The operating principle of such a cell is illustrated in Figure. Oxygen supplied at the cathode (air electrode) reacts with incoming electrons from the external circuit to form oxide ions, which migrate to the anode (fuel electrode) through the oxide ion conducting electrolyte. At the anode, oxide ions combine with hydrogen (and/or carbon monoxide) in the fuel to form water (and/or carbon dioxide), liberating electrons. Electrons (electricity) flow from the anode through the external circuit to the cathode. The materials for the cell components are selected based on suitable electrical conducting properties required of these components to perform their intended cell functions;

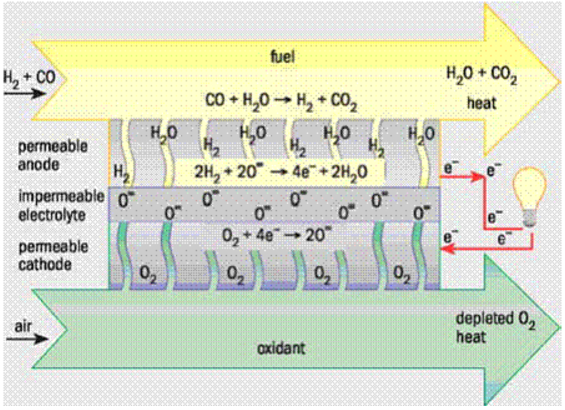


Fig. Operating principle of a solid oxide fuel cell.

adequate chemical and structural stability at high temperatures encountered during cell operation as well as during cell fabrication; minimal reactivity and inter diffusion among different components; and matching thermal expansion among different components.

MATERIALS AND CELL DESIGNS

ELECTROLYTE

Yttrium-doped zirconium oxide (YSZ) remains the most widely used material for the electrolyte in SOFCs because of its sufficient ionic conductivity, chemical stability, and mechanical strength. The only drawback of stabilized YSZ is the low ionic conductivity in the lower cell operation temperature regime, below about 750°C (1382°F). Two solutions that have been tried to resolve this problem are to decrease the thickness of the YSZ electrolyte and to find other materials to replace the yttrium. Scandium-doped zirconium oxide has higher conductivity than YSZ but high cost of scandium and detrimental ageing effects in scandium doped zirconium oxide make it less attractive in commercializing SOFCs. Gadolinium- or samarium-doped cerium oxide materials possess higher oxide ion conductivity compared to zirconium based materials. However, cerium oxide based materials, under reducing conditions at high temperatures, exhibit significant electronic conductivity and dimensional change. Operation at temperatures below about 600°C (1112°F) overcomes this problem, and cerium oxide based materials are successfully being used as electrolyte in SOFCs by Ceres Power Limited (UK). In addition to the traditionally used oxides of zirconium and cerium, other mixed oxides also provide an opportunity to develop oxide ion conducting electrolytes. One mixture, containing among others gallium oxide, has attracted attention as an electrolyte. However, it has two drawbacks: uncertain cost of gallium, and uncertain chemical and mechanical stability of the oxide. In spite of these drawbacks, Mitsubishi Materials Corporation (Japan) is using this as the electrolyte in its SOFCs and has successfully built and tested up to 10-kW size SOFC power systems.

CATHODE

The oxidant gas is air or oxygen at the SOFC cathode, and the electrochemical reduction of oxygen requires a series of elementary reactions and involves the transfer of multiple electrons. The SOFC cathode must meet the requirements of high catalytic activity for oxygen molecule dissociation and oxygen reduction, high electronic conductivity, chemical and dimensional stability in environments encountered during cell fabrication and cell operation, thermal expansion match with other cell components, and compatibility and minimum reactivity with the electrolyte and the interconnection.

Finally, the cathode must have a stable, porous microstructure so that gaseous oxygen can readily diffuse through the cathode to the cathode/electrolyte interface. These stringent electrochemical and mechanical requirements greatly restrict the number of suitable candidate materials. Lanthanum manganite, which, when substituted with low valence elements such as calcium or strontium, has good electronic conduction. Moreover, it possesses adequate electrocatalytic activity, a reasonable thermal expansion match to YSZ, and stability in the SOFC cathode operating environment. For SOFCs operating at substantially lower temperatures, such as 650 to 800°C (1202 to 1472°F), alternative cathode materials, typically containing transition metals such as cobalt, iron, and/or nickel, have been developed and optimized for better performance. In general, these materials offer higher oxide ion diffusion rates and exhibit faster oxygen reduction kinetics at the cathode/electrolyte interface compared with lanthanum manganite. However, the thermal expansion coefficient of cobaltites is much higher than that of the YSZ electrolyte, and the electrical conductivities of ferrites and nickelites are low. Nevertheless, promising results have been reported using these materials, though in many cases the improved cathodic performance is found to decrease during the cell lifetime as a result of chemical or micro structural instability.

Minimization of cathodic polarization losses is one of the biggest challenges to be overcome in obtaining high, stable power densities from lower temperature SOFCs. However, these materials are very reactive toward YSZ. Therefore, a thin layer, generally of a cerium oxide based material, is used to reduce the chemical reaction between the cathode and YSZ. Microstructure also plays a major role in the cathode polarization; this is particularly true when a composite cathode, which shows a better performance compared to a single composition cathode, is used. It has been shown that polarization resistance depends upon the grain size of the ionic conductor in the composite electrode and the volume fraction of porosity.

ANODE

The anode must be an excellent catalyst for the oxidation of fuel (hydrogen, carbon dioxide), stable in the reducing environment of the fuel, electronically conducting, and must have sufficient porosity to allow the transport of the fuel to and the transport of the products of fuel oxidation away from the electrolyte/anode interface where the fuel oxidation reaction takes place. The other requirements include matching of its thermal expansion coefficient with that of the electrolyte and interconnect; integrity of porosity for gas permeation; chemical stability with the electrolyte and interconnect; and applicability to use with versatile fuels and impurities. In addition, cost effectiveness is always a factor for commercialization. Nickel-YSZ composites are the most commonly used anode materials for SOFCs. Nickel is an excellent catalyst for fuel oxidation; however, it possesses a high thermal expansion coefficient, and exhibits coarsening of microstructure due to metal aggregation through grain growth at cell operation temperatures. YSZ in the anode constrains nickel aggregation and prevents sintering of the nickel particles, decreases the effective thermal expansion coefficient bringing it closer to that of the electrolyte, and provides better adhesion of the anode with the electrolyte. In these anodes, nickel has dual roles of the catalyst for hydrogen oxidation and the electrical current conductor. In addition, it is also highly active for the steam reforming of methane. This catalytic property is exploited in the so-called internal reforming SOFCs that can operate on fuels composed of mixtures of methane and water. Although nickel is an excellent hydrogen oxidation and methane-steam reforming catalyst, it also catalyzes the formation of carbon from hydrocarbons under reducing conditions. Unless sufficient amounts of steam are present along with the hydrocarbon to remove carbon from the nickel surface, the anode may be destroyed. As a result, even when using methane as the fuel, relatively high steam-to-carbon ratios are needed to suppress this deleterious reaction. Unfortunately, due to the high catalytic activity of nickel for hydrocarbon cracking, this approach does not work for higher hydrocarbons, and it is generally not possible to operate nickel-based anodes on higher hydrocarbon-containing fuels without pre-reforming with steam or oxygen. In spite of this drawback, a nickel-YSZ composite remains the most

commonly utilized anode material for SOFCs and is satisfactory for cells operating on clean, reformed fuel.
However, advanced SOFC designs place additional constraints on the anode, such as tolerance of oxidizing environments and/or the ability to tolerate significant quantities of sulphur and/or hydrocarbon species in the fuel stream. Alternative materials, such as cerium oxide or strontium titanate/cerium oxide mixtures, have yielded some promising results in these designs, but the benefits obtained in terms of sulphur, hydrocarbon and/or redox tolerance are counterbalanced by other limitations (such as the difficulty of integrating such materials with existing cell and stack fabrication processes and materials). Copper based anodes have also been proposed for intermediate temperature (<800°C; <1472°F) SOFCs intended to operate directly on hydrocarbon fuels without prior reformation, but the lack of catalytic activity for oxidation of fuel in copper and sintering of copper at the cell operating temperatures have limited their use in practical SOFCs.

Interconnect

Since a single cell only produces voltage less than 1 V and power around 1 W/cm², many cells are electrically connected together in a cell stack to obtain higher voltage and power. To connect multiple cells together, an interconnection is used in SOFC stacks. The requirements of the interconnection are the most severe of all cell components and include: nearly 100 percent electronic conductivity; stability in both oxidizing and reducing atmospheres at the cell operating temperature since it is exposed to air (or oxygen) on the cathode side and fuel on the anode side; low permeability for oxygen and hydrogen to minimize direct combination of oxidant and fuel during cell operation; a thermal expansion coefficient close to that of the cathode and the electrolyte; and non-reactivity with other cell materials. To satisfy these requirements, doped lanthanum chromite is used as the interconnection for cells intended for operation at about 1000°C (1832°F). In cells intended for operation at lower temperatures (<800°C; <1412°F), it is possible to use oxidation-resistant metallic materials for the interconnection. Compared to lanthanum chromite ceramic interconnects, metallic alloys offer advantages such as improved manufacturability, significantly lower raw material and fabrication costs, and higher electrical and thermal conductivity. But to be useful for the interconnect application, the metallic alloys must satisfy additional requirements, including resistance to surface oxidation and corrosion in a dual atmosphere (simultaneous exposure to oxidizing and reducing atmospheres), thermal expansion matching to other stack components (particularly for stacks using a rigid seal design), chemical compatibility with other materials in contact with the interconnect, such as seals and cell materials, high electrical conductivity not only through the bulk material but also in in-situ-formed oxide scales, mechanical reliability and durability at the cell operating temperature, and strong adhesion between the as-formed oxide scale and the underlying alloy substrate. Ferritic stainless steels are the most promising candidates, owing to the fact that some alloys in this family offer a protective and conductive chromium-based oxide scale, appropriate thermal expansion behavior, ease of manufacturing and low cost. Several new ferritic stainless steels have been developed specifically for SOFC interconnects. Although these alloys demonstrate improved performance over traditional compositions, several critical issues remain; among these are chromium oxide scale evaporation and subsequent poisoning of cathodes; scale electrical resistivity in the long term; corrosion and spalling under interconnect exposure conditions; and compatibility with the adjacent components such as seals and electrical contact layers. To overcome some of these problems, some surface coatings can be applied onto metallic interconnects to minimize scale growth, electrical resistance and chromium volatility.

HYBRID POWER SYSTEMS:

INTRODUCTION

Electrical energy requirements for many remote applications are too large to allow the cost-effective use of stand-alone or autonomous PV systems. In these cases, it may prove more feasible to combine several different types of power sources to form what is known as a "hybrid" system. To date, PV has been effectively combined with other types of power generators such as wind, hydro, thermoelectric, petroleum-fueled and even hydrogen. The selection process for hybrid power source types at a given site can include a combination of many factors including site topography, seasonal availability of energy sources, cost of source implementation, cost of energy storage and delivery, total site energy requirements, etc.

- Hybrid power systems use local renewable resource to provide power.
- Village hybrid power systems can range in size from small household systems (100 Wh/day) to ones supplying a whole area (10's MWh/day).
- They combine many technologies to provide reliable power that is tailored to the local resources and community.
- Potential components include: PV, wind, micro-hydro, river-run hydro, biomass, batteries and conventional generators.

A. Configuration of hybrid system

Figure shows the basic configuration of hybrid system discussed in this study. The hybrid system was consisted of reduction gear, main-motor (EM1), sub- motor (EM2), engine, power controller and battery. It was supposed that a double-motor system was prepared for the driving system discussed in this study. At first, acceleration was assisted by was applied only by main motor when the driving speed was low, while the corporation by two motors was often achieved to drive the system.
If the SOC (state of charge) of battery was decreased below the specific threshold, the battery was charged by sub-motor. This operation was priority to over other actions. Figure 2 shows the modified configuration of hybrid system proposed in this study.

In the modified system, CVT was utilized to keep constant revolution numbers of the sub-motor when the sub-motor contributed to assist the system.

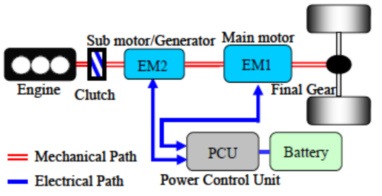
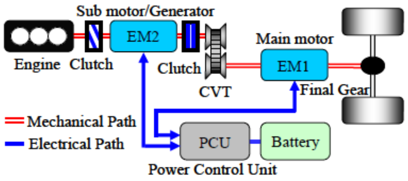


Figure 1 Schematic view of double motor hybrid system



Schematic view of double motor hybrid system with CVT

Petroleum-fueled engine generators (Gensets)

Petroleum-fueled gensets (operating continuously in many cases) are presently the most common method of supplying power at sites remote from the utility grid such as villages, lodges, resorts, cottages and a variety of industrial sites including telecommunications, mining and logging camps, and military and other government operated locations. Although gensets are relatively inexpensive in initial cost, they are not inexpensive to operate. Costs for fuel and maintenance can increase exponentially when these needs must be met in a remote location. Environmental factors such as noise, carbon oxide emissions, transport and storage of fuel must also be considered.

Figure Hybrid PV/Generator System Example; Courtesy Photron Canada Inc., Location: Sheep Mountain Interpretive Centre, Parks Canada Kluone National Park, Yukon Territories, Canada, 63° North Latitude; Components shown include: generator (120/240 V), battery (deep cycle industrial rated @ ± 10 kWh capacity), DC to AC stand-alone inverter (2500 W @ 120 V output), miscellaneous safety + control equipment including PV array disconnect, PV control/regulator, automatic generator start/-stop control, DC/AC system metering etc.; -Components not shown: PV array (800 W peak).

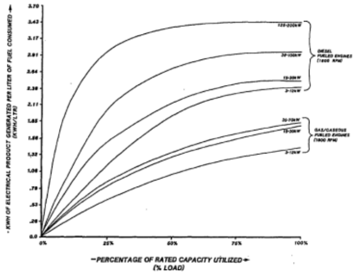


Figure Genset fuel efficiency vs. capacity utilized.

Fuel to power conversion efficiencies may be as high as 25% (for a diesel fueled unit operating at rated capacity). Under part load conditions, however, efficiencies may decline to a few percent. Considerable waste heat is therefore available and may be utilized for other requirements such as space and/or water heating.

Why a PV/Genset hybrid?

PV and genset systems do not have much in common. It is precisely for this reason that they can be mated to form a hybrid system that goes far in overcoming the drawbacks to each technology. Table 10.1 lists the respective advantages and disadvantages. As the sun is a variable energy source, PV system designs are increased in size (and therefore cost) to allow for a degree of system autonomy. Autonomy is required to allow for provision of reliable power during "worst case" situations, which are usually periods of adverse weather, seasonally low solar insolation values or an unpredicted increased demand for power. The addition of autonomy to the system is accomplished by increasing the size of the PV array and its requisite energy storage system (the battery).When a genset is added, additional battery charging and direct AC load supply capabilities are provided. The need to build in system autonomy is therefore greatly reduced. When energy demands cannot be met by the PV portion of the system for any reason, the genset is brought on line to provide the required backup power. Substantial cost savings can be achieved and overall system reliability is enhanced.PV/genset hybrid systems have been utilized at sites with daily energy requirements ranging from as low as 1 kWh per day to as high as 1 MWh per day, which illustrates their extreme flexibility. They are a proven and reliable method for efficient and cost effective power supply at remote sites.

PV/genset hybrid system description

The PV/genset hybrid utilizes two diverse energy sources to power a site's loads. The PV array is employed to generate DC energy that is consumed by any existing DC loads, with the balance (if any) being used to charge the system's DC energy storage battery.

The PV array is automatically on line and feeding power into the system whenever solar insolation is available and continues to produce system power during daylight hours until its rate of production exceeds what all existing DC loads and the storage battery can absorb. Should this occur, the array is inhibited by the system controller from feeding any further energy into the loads or battery. A genset is employed to generate AC energy that is consumed by any existing AC loads, with the balance (if any) being used by the battery charger to generate DC energy that is used in the identical fashion to that described for the PV array above.

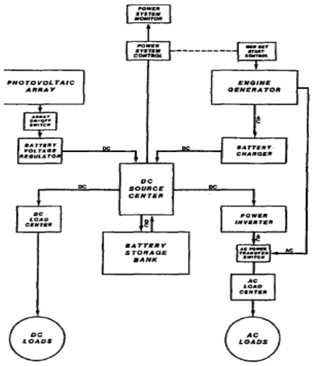


Figure Block diagram of a hybrid PV-Genset system.

At times when the genset is not running, all site AC power is derived from the system's power conditioner or inverter, which automatically converts system DC energy into AC energy whenever AC loads are being operated. The genset is operated cyclically in direct response to the need for maintaining a suitable state of charge level in the system's battery storage bank.

Other PV/hybrid types

Certain specific site locations may offer access to other forms of power generation. Access to flowing water presents the potential for hydro power. Access to consistent wind at sufficient velocity presents the potential for wind power. PV/hydro and PV/wind hybrid systems have been utilized at sites with daily energy requirement ranges similar to those described for PV/genset hybrids. Their use, however, is much more site dependent, as their energy source is a factor of that locations' topography.

PV/Thermoelectric generator hybrid systems have been used effectively at sites whose daily energy requirement is relatively low, ranging from 1 to 20 kWh per day. Propane is the fuel source for the thermoelectric process, and conversion efficiencies of up to 8% can be achieved. Considerable waste heat is therefore available which may be utilized for other requirements. In cold climates, this heat is often used to maintain the battery storage system at desired temperature levels.

Architectural Integration

Motivation

The last two decades have brought significant changes to the design profession. In the wake of traumatic escalations in energy prices, shortages, embargoes and war along with heightened concerns over pollution, environmental degradation and resource depletion, awareness of the environmental impact of our work as design professionals has dramatically increased. In the process, the shortcomings of yesterday's buildings have also become increasingly clear: inefficient electrical and climate conditioning systems squander great amounts of energy. Combustion of fossil fuels on-site and at power plants add greenhouse gases, acid rain and other pollutants to the environment. Inside, many building materials, furnishings and finishes give off toxic by-products contributing to indoor air pollution. Poorly designed lighting and ventilation systems can induce headaches and fatigue.Architects with vision have come to understand it is no longer the goal of good design to simply create a building that is aesthetically pleasing - buildings of the future must be environmentally responsive as well. They have responded by specifying increased levels of thermal insulation, healthier interiors, higher-efficiency lighting, better glazing and HVAC (heating, ventilation and air conditioning) equipment, air-to-air heat exchangers and heat-recovery ventilation systems. Significant advances have been made and this progress is a very important first step in the right direction. However, it is not enough. For the developed countries to continue to enjoy the comforts of the late twentieth century and for the developing world to ever hope to attain them, sustainability must become the cornerstone of our design philosophy. Rather than merely using less non-renewable fuels and creating less pollution, we must come to design sustainable buildings that rely on renewable resources to produce some or all of their own energy and create no pollution. One of the most promising renewable energy technologies is photovoltaic's. Photovoltaics (PV) is a truly elegant means of producing electricity on site, directly from the sun, without concern for energy supply or environmental harm. These solid-state devices simply make electricity out of sunlight, silently with no maintenance, no pollution and no depletion of materials. Photovoltaics are also exceedingly versatile - the same technology that can pump water, grind grain and provide communications and village electrification in the developing world can produce electricity for the buildings and distribution grids of the industrialized countries.There is a growing consensus that distributed photovoltaic systems which provide electricity at the point of use will be the first to reach widespread commercialization. Chief among these distributed applications are PV power systems for individual buildings. Interest in the building integration of photovoltaics, where the PV elements actually become an integral part of the building, often serving as the exterior weathering skin, is growing world-wide. PV specialists from some 15 countries are working within the International Energy Agency's Task 16 on a 5-year effort to optimize these systems and architects are now beginning to explore innovative ways of incorporating solar electricity into their building designs.

Planning context of an energy conscious design project

The possibilities of an active and passive solar energy use in buildings is the facade or into different building components, such as a photovoltaic rooftile. Such an integration makes sense for various reasons: ·The solar irradiation is a distributed energy source; the energy demand is distributed as well.·The building envelopes supply sufficient area for PV generators and therefore

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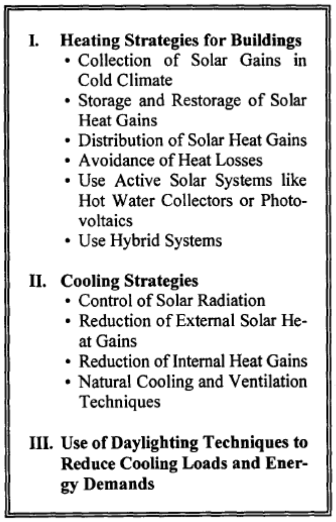


I. Heating Strategies for Buildings
- Collection of Solar Gains in Cold Climate
- Storage and Restorage of Solar Heat Gains
- Distribution of Solar Heat Gains
- Avoidance of Heat Losses
- Use Active Solar Systems like Hot Water Collectors or Photovoltaics
- Use Hybrid Systems

II. Cooling Strategies
- Control of Solar Radiation
- Reduction of External Solar Heat Gains
- Reduction of Internal Heat Gains
- Natural Cooling and Ventilation Techniques

III. Use of Daylighting Techniques to Reduce Cooling Loads and Energy Demands

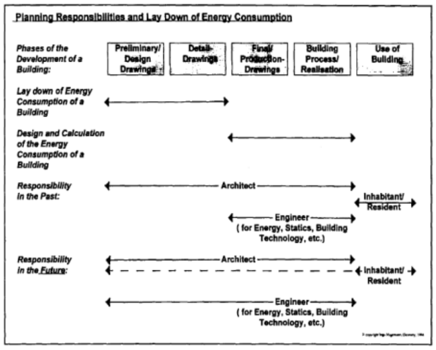
Active and Passive Solar Design Principles

In order to use PV together with other available techniques of active and passive solar energy, it must be considered that some techniques fit well together and others exclude each other. For example: As a kind of a "passive cooling system", creepers are used for covering the south facade of building. The leaves evaporate water and provide shade on the facade. This helps to avoid penetration of direct sunlight and reduces the temperature in the rooms behind the facade. At the same time the leaves create shading on PV modules that may be mounted on the facade resulting in a far lower electricity production. To avoid such design faults it is necessary to compare and evaluate the different techniques that are available for creating an energy conscious building. An overall energy concept for a building should be made at the beginning of the design process. Therefore, the architect and the other experts involved in the design and planning process need to work together right from the beginning of the design and planning process. All together they have to search right from the beginning for the best design for a building project.

Photovoltaics and Architecture

Photovoltaic's and Architecture are a challenge for a new generation of buildings. Installations fulfilling a number of technical approaches do not automatically represent aesthetical solutions. Collaboration between engineers and architects is essential to create outstanding overall designs. This again will support the wide use of PV. These systems will acquire a new image, ceasing to be a toy or a solar module reserved for a mountain chalet but becoming a modern building unit, integrated into the design of roofs and facades. The architects, together with the engineers involved are asked to integrate PV at least on four levels during the planning and realisation of a building:
· Design of a building (shape, size, orientation, colour)
· Mechanical integration (multi functionality of a PV element)
· Electrical integration (grid connection and/or direct use of the power)
· Maintenance and operation control of the PV system must be

integrated into the usual building maintenance and control.



Planning Responsibilities and Lay Down of Energy

Consumption.

MICROGRID CONCEPT

To realize the emerging potential of distributed generation one must take a system approach which views generation and associated loads as a subsystem or a "microgrid". During disturbances, the generation and corresponding loads can separate from the distribution system to isolate the microgrid's load from the disturbance (and thereby maintaining service) without harming the transmission grid's integrity.
The difficult task is to achieve this functionality without extensive custom engineering and still have high system reliability and generation placement flexibility. To achieve this we promote a peer-to-peer and plug-and-play model for each component of the microgrid. The peer-to-peer concept insures that there are no components, such as a master controller or central storage unit that is critical for operation of the microgrid. This implies that the microgrid can continue operating with loss of any component or generator. With one additional source (N+1) we can insure complete functionality with the loss of any source.
Plug-and-play implies that a unit can be placed at any point on the electrical system without reengineering the controls. Plug-and-play functionality is much akin to the flexibility one has when using a home appliance.
That is it can be attached to the electrical system at the location where it is needed. The traditional model is to cluster generation at a single point that makes the electrical application simpler. The plug-and-play model facilitates placing generators near the heat loads thereby allowing more effective use of waste heat without complex heat distribution systems such as steam and chilled water pipes.
This ability to island generation and loads together has the potential to provide a higher local reliability than that provided by the power system as a whole. Smaller units, having power ratings in thousands of watts, can provide even higher reliability and fuel efficiency. These units can create microgrid services at customer sites such as office buildings, industrial parks and homes. Since the smaller units are modular, site management could decide to have more units (N+) than required by the electrical/heat load, providing local, online backup if one or more of the operating units failed. It is

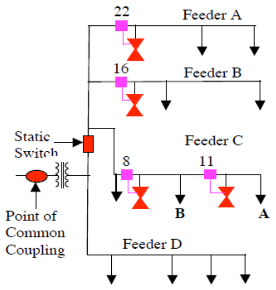


Figure 2 Microgrid

Also much easier to place small generators near the heat loads thereby allowing more effective use of waste heat. Basic Microgrid architecture is shown in figure 2. This consists of a group of radial feeders, which could be part of a distribution system or a building's electrical system. There is a single point of connection to the utility called point of common coupling. Some feeders, (Feeders A-C) have sensitive loads, which require local generation.

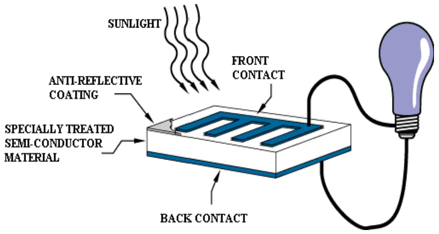
The noncritical load feeders do not have any local generation. In our example this is Feeder D. Feeders A-C can island from the grid using the static switch which can separate in less than a cycle. In this example there are four micro sources at nodes 8, 11, 16 and 22, which control the operation using only local voltages and currents measurments. When there is a problem with the utility supply the static switch will open, isolating the sensitive loads from the power grid. Feeder D loads ride through the event. It is assumed that there is sufficient generation to meet the loads' demand. When the Microgrid is grid-connected power from the local generation can be directed to feeder D.

PHOTOVOLTAIC TECHNOLOGY

Photovoltaic's is the field of technology and research related to the devices which directly convert sunlight into electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic effect involves the creation of voltage in a material upon exposure to electro magnetic radiation..The photovoltaic effect was first noted by a French physicist, Edmund Becquerel, in 1839, who found that certain materials would produce small amounts of electric current when exposed to light. In 1905, Albert Einstein described the nature of light and the photoelectric effect on which photovoltaic technology is based, for which he later won a Nobel prize in physics. The first photovoltaic module was built by Bell Laboratories in 1954. It was billed as a solar battery and was mostly just a curiosity as it was too expensive to gain widespread use. In the 1960s, the space industry began to make the first serious use of the technology to provide power aboard spacecraft. Through the space programs, the technology advanced, its reliability was established, and the cost began to decline. During the energy crisis in the 1970s, photovoltaic technology gained recognition as a source of power for non-space applications.The solar cell is the elementary building block of the photovoltaic technology. Solar cells
are made of semiconductor materials, such as silicon. One of the properties of semiconductors that makes them most useful is that their conductivity may easily be modified by introducing impurities into their crystal lattice. For instance, in the fabrication of a photovoltaic solar cell, silicon, which has four valence electrons, is treated to increase its conductivity. On one side of the cell, the impurities, which are phosphorus atoms with five valence electrons (n-donor), donate weakly bound valence electrons to the silicon material, creating excess negative charge carriers. On the other side, atoms of boron with three valence electrons (p-donor) create a greater affinity than silicon to attract electrons. Because the p-type silicon is in intimate contact with the n-type silicon a p-n junction is established and a diffusion of electrons occurs from the region of high electron concentration (the n-type side) into the region of low electron concentration (p-type side).

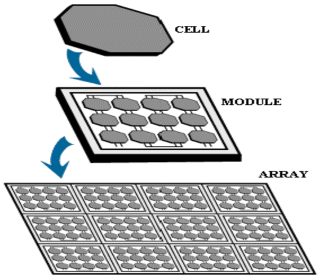
When the electrons diffuse across the p-n junction, they recombine with holes on the p-type side. However, the diffusion of carriers does not occur indefinitely, because the imbalance of charge immediately on either sides of the junction originates an electric field. This electric field forms a diode that promotes current to flow in only one direction.

Ohmic metal-semiconductor contacts are made to both the n-type and p-type sides of the solar cell, and the electrodes are ready to be connected to an external load. When photons of light fall on the cell, they transfer their energy to the charge carriers. The electric field across the junction separates photo-generated positive charge carriers (holes) from their negative counterpart (electrons). In this way an electrical current is extracted once the circuit is closed on an external load.



SOLAR CELL

The photovoltaic effect was reported by Edmund Bequerel in 1839 when he observed that the action of light on a silver coated platinum electrode immersed in electrolyte produced an electric current. Forty years later the first solid state photovoltaic devices were constructed by workers investigating the recently discovered photoconductivity of selenium. In 1876 William Adams and Richard Day found that a photocurrent could be produced in a sample of selenium when contacted by two heated platinum contacts. The photovoltaic action of the selenium diverted from its photoconductive action in that a current was produced spontaneously by the action of light. No external power supply was needed. In this early photovoltaic device, a rectifying junction had been formed between the semiconductor and the metal contact. In 1894, Charles Fritts prepared what was probably the first large area solar cell by pressing a layer of selenium between gold and another metal. In the following years photovoltaic effects were observed in copper{copper oxide thin film structures, in lead sulphide and thallium sulphide. These early cells were thin film Schottky barrier devices, where a semitransparent layer of metal deposited on top of the semiconductor provided both the asymmetric electronic junction, which is necessary for photovoltaic action, and access to the junction for the incident light. The photovoltaic effect of structures like this was related to the existence of a barrier to current flow at one of the semiconductor {metal interfaces (i.e., rectifying action) by Goldman and Brodsky in 1914. Later, during the 1930s, the theory of metal{semiconductor barrier layers was developed by Walter Schottky, Neville Mott and others.However, it was not the photovoltaic properties of materials like selenium which excited researchers, but the photoconductivity. The fact that the current produced was proportional to the intensity of the incident light, and related to the wavelength in a definite way meant that photoconductive materials were ideal for photographic light meters. The photovoltaic electin barrier structures was an added benefit, meaning that the light meter could operate without a power supply. It was not until the 1950s, with the development of good quality silicon wafers for applications in the new solid state electronics, that potentially useful quantities of power were produced by photovoltaic devices in crystalline silicon.In the 1950s, the development of silicon electronics followed the discovery of a way to manufacture p{n junctions in silicon. Naturally n type silicon wafers developed a p type skin when exposed to the gas boron trichloride. Part of the skin could be etched away to give access to the n type layer beneath. These p{n junction structures produced much better rectifying action than Schottky barriers, and better photovoltaic behaviour. The first silicon solar cell was reported by Chapin, Fuller and Pearson in 1954 and converted sunlight with an efficiency of 6%, six times higher than the best previous attempt. That figure was to rise significantly over the following years and decades but, at an estimated production cost of some $200 per Watt, these cells were not seriously considered for power generation for several decades. Nevertheless, the early silicon solar cell did introduce the possibility of power generation in remote locations where fuel could not easily be delivered. The obvious application was to satellites where the requirement of reliability and low weight made the cost of the cells unimportant and during the 1950s and 60s, silicon solar cells were widely developed for applications in space.Also in 1954, a cadmium sulphide p{n junction was produced with an efficiency of 6%, and in the following years studies of p{n junction photovoltaic devices in gallium arsenide, indium phosphide and cadmium telluride were stimulated by theoretical work indicating that these materials would offer a higher efficiency. However, silicon remained and remains the foremost photovoltaic material, benefiting from the advances of silicon technology for the microelectronics industry. Short histories of the solar cell are given elsewhere. In the 1970s the crisis in energy supply experienced by the oil-dependent western world led to a sudden growth of interest in alternative sources of energy, and funding for research and development in those areas. Photovoltaics was a subject of intense interest during this period, and a range of strategies for producing photovoltaic devices and materials more cheaply and for improving device efficiency were explored. Routes to lower cost included photo electrochemical junctions, and alternative materials such as polycrystalline silicon, amorphous silicon, other `thin _lm' materials and organic conductors. Strategies for higher efficiency included tandem and other multiple band gap designs. Although none of these led to widespread commercial development, our understanding of the science of photovoltaics is mainly rooted in this period..During the 1990s, interest in photovoltaics expanded, along with growing awareness of the need to secure sources of electricity alternative to fossil fuels. The trend coincides with the widespread deregulation of the electricity markets and growing recognition of the viability of decentralized power. During this period, the economics of photovoltaics improved primarily through economies of scale. In the late 1990s the photovoltaic production expanded at a rate of 15{25% per annum, driving a reduction in cost. Photovoltaics first became competitive in contexts where conventional electricity supply is most expensive, for instance, for remote low power applications such as navigation, telecommunications, and rural electrification and for enhancement of supply in grid-connected loads at peak use as prices fall, new markets are opened up. An important example is building integrated photovoltaic applications, where the cost of the photovoltaic system is offset by the savings in building materials.There are several types of solar cells. However, more than 90 % of the solar cells currently made worldwide consist of wafer-based silicon cells. They are either cut from a single crystal rod or from a block composed of many crystals and are correspondingly called mono-crystalline or multi-crystalline silicon solar cells. Wafer-based silicon solar cells are approximately 200 µm thick. Another important family of solar cells is based on thin-films, which are approximately 1-2 µm thick and therefore require significantly less active, semiconducting material. Thin-film solar cells can be manufactured at lower cost in large production quantities; hence their market share will likely increase in the future. However, they indicate lower efficiencies than wafer-based silicon solar cells, which mean that more exposure surface and material for the installation is required for a similar performance. A number of solar cells electrically connected to each other and mounted in a single support structure or frame is called a ‘photovoltaic module’. Modules are designed to supply electricity at a certain voltage, such as a common 12 volt system. The current produced is directly dependent on the intensity of light reaching the module. Several modules can be wired together to form an array. Photovoltaic modules and arrays produce direct-current electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination.



ELECTRICAL CONNECTION OF THE CELLS

The electrical output of a single cell is dependent on the design of the device and the Semi-conductor material(s) chosen, but is usually insufficient for most applications. In order to provide the appropriate quantity of electrical power, a number of cells must be electrically connected. There are two basic connection methods: series connection, in which the top contact of each cell is connected to the back contact of the next cell in the sequence, and parallel connection, in which all the top contacts are connected together, as are all the bottom contacts. In both cases, this results in just two electrical connection points for the group of cells.Series connection:Figure shows the series connection of three individual cells as an example and the resultant group of connected cells is commonly referred to as a series string. The current output of the string is equivalent to the current of a single cell, but the voltage output is increased, being an addition of the voltages from all the cells in the string (i.e. in this case, the voltage output is equal to 3Vcell).

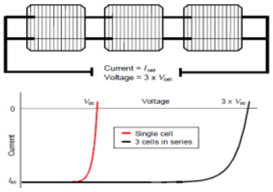


Fig. Series connection of cells, with resulting current–voltage characteristic.

It is important to have well matched cells in the series string, particularly with respect to current. If one cell produces a significantly lower current than the other cells (under the same illumination conditions), then the string will operate at that lower current level and the remaining cells will not be operating at their maximum power points.
Figure shows the parallel connection of three individual cells as an example. In this case, the current from the cell group is equivalent to the addition of the current from each cell (in this case, 3 Icell), but the voltage remains equivalent to that of a single cell.As before, it is important to have the cells well matched in order to gain maximum output, but this time the voltage is the important parameter since all cells must be at the same operating voltage. If the voltage at the maximum power point is substantially different for one of the cells, then this will force all the cells to operate off their maximum power point, with the poorer cell being pushed towards its open-circuit voltage value and the better cells to voltages below the maximum power point voltage. In all cases, the power level will be reduced below the optimum.

THE PHOTOVOLTAIC ARRAY

A PV array consists of a number of PV modules, mounted in the same plane and electrically connected to give the required electrical output for the application. The PV array can be of any size from a few hundred watts to hundreds of kilowatts, although the larger systems are often divided into several electrically independent sub arrays each feeding into their own power conditioning system.

MOUNTING STRUCTURE

The main purpose of the mounting structure is to hold the modules in the required position without undue stress. The structure may also provide a route for the electrical wiring and may be free standing or part of another structure (e.g. a building). At its simplest, the mounting structure is a metal framework, securely fixed into the ground. It must be capable of withstanding appropriate environmental stresses, such as wind loading, for the location. As well as the mechanical issues, the mounting has an influence on the operating temperature of the system, depending on how easily heat can be dissipated by the module.

TILT ANGLE AND ORIENTATION

The orientation of the module with respect to the direction of the Sun determines the intensity of the sunlight falling on the module surface. Two main parameters are defined to describe this. The first is the tilt angle, which is the angle between the plane of the module and the horizontal. The second parameter is the azimuth angle, which is the angle between the plane of the module and due south (or sometimes due north depending on the definition used). Correction of the direct normal irradiance to that on any surface can be determined using the cosine of the angle between the normal to the Sun and the module plane.The optimum array orientation will depend on the latitude of the site, prevailing weather conditions and the loads to be met.It is generally accepted that, for low latitudes, the maximum annual output is obtained when the array tilt angle is roughly equal to the latitude angle and the array faces due south (in the northern hemisphere) or due north (for the southern hemisphere). For higher latitudes, such as those in northern Europe, the maximum output is usually obtained for tilt angles of approximately the latitude angle minus 10–15 degrees. The optimum tilt angle is also affected by the proportion of diffuse radiation in the sunlight, since diffuse light is only weakly directional. Therefore, for locations with a high proportion of diffuse sunlight, the effect of tilt angle is reduced.
However, although this condition will give the maximum output over the year, there can be considerable variation in output with season. This is particularly true in high-latitude locations where the day length varies significantly between summer and winter. Therefore, if a constant or reasonably constant load is to be met or, particularly, if the winter load is higher than the summer load, then the best tilt angle may be higher in order to boost winter output. Prevailing weather conditions can influence the optimisation of the array orientation if they affect the sunlight levels available at certain times of the day. Alternatively, the load to be met may also vary during the day and the array can be designed to match the output with this variable demand by varying the azimuth angle. Notwithstanding the ability to tailor the output profile by altering the tilt and azimuth angles, the overall array performance does not vary substantially for small differences in array orientation. Figure shows the percentage variation in annual insolation levels for the location of London as tilt angle is varied between 0 and 90 degrees and azimuth angle is varied between –45o (south east) and +45o (south west). The maximum insolation level is obtained for a south-facing surface at a tilt angle of about 35 degrees, as would be expected for a latitude of about 51oN. However, the insolation level varies by less than 10% with changing azimuth angle at this tilt angle. A similarly low variation is observed for south facing surfaces for a variation of +/- 30 degrees from the optimum tilt angle.

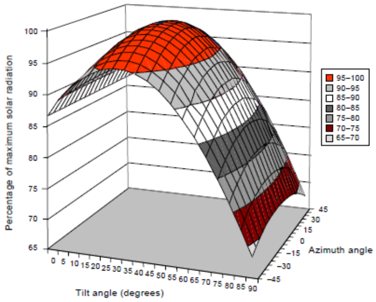


Fig. Percentage variation of annual sunlight levels as a function of tilt angle and azimuth angle.

The calculations were carried out for the location of London using Meteonorm Version 3.0. The final aspect to consider when deciding on array orientation is the incorporation in the support structure. For building-integrated applications, the system orientation is also dictated by the nature of the roof or façade in which it is to be incorporated. It may be necessary to trade off the additional output from the optimum orientation against any additional costs that might be incurred to accomplish this. The aesthetic issues must also be considered.

SUN-TRACKING/CONCENTRATOR SYSTEMS

The previous section has assumed a fixed array with no change of orientation during operation. This is the usual configuration for a flat-plate array. However, some arrays are designed to track the path of the Sun. This can account fully for the sun's movements by tracking in two axes or can account partially by tracking only in one axis, from east to west. For a flat-plate array, single-axis tracking, where the array follows the east-west movement of the Sun, has been shown to increase the output by up to 30% for a location with predominantly clear sky conditions.

Two-axis tracking, where the array follows both the daily east-west and north-south movement of the sun, could provide a further increase of about 20% (Lepley, 1990). For locations where there are frequent overcast conditions, such as northern Europe, the benefits of tracking are considerably less. It is usually more economical to install a larger panel for locations with less than about 3000 hours of direct sunshine per annum. For each case, the additional output from the system must be compared to the additional cost of including the tracking system, which includes both the control system and the mechanism for moving the array. For concentrator systems, the system must track the Sun to maintain the concentrated light falling on the cell. The accuracy of tracking, and hence the cost of the tracking system, increases as the concentration ratio increases.

SHADING

Shading of any part of the array will reduce its output, but this reduction will vary in magnitude depending on the electrical configuration of the array. Clearly, the output of any cell or module which is shaded will be reduced according to the reduction of light intensity falling on it. However, if this shaded cell or module is electrically connected to other cells and modules which are unshaded, their performance may also be reduced since this is essentially a mismatch situation. For example, if a single module of a series string is partially shaded, its current output will be reduced and this will then dictate the operating point of the whole string.

If several modules are shaded, the string voltage may be reduced to the point where the open-circuit voltage of that string is below the operating point of the rest of the array, and then that string will not contribute to the array output. If this is likely to occur, it is often useful to include a blocking diode for string protection, as discussed earlier.

Thus, the reduction in output from shading of an array can be significantly greater than the reduction in illuminated area, since it results from• the loss of output from shaded cells and modules;• the loss of output from illuminated modules in any severely shaded strings that cannot maintain operating voltage; and• the loss of output from the remainder of the array because the strings are not operating at their individual maximum power points.For some systems, such as those in a city environment, it may be impossible to avoid all shading without severely restricting the size of the array and hence losing output at other times. In these cases, good system design, including the optimum interconnection of modules, the use of string or module inverters and, where appropriate, the use of protection devices such as blocking diodes, can minimize the reduction in system output for the most prevalent shading conditions.

THE PHOTOVOLTAIC SYSTEM

A PV system consists of a number of interconnected components designed to accomplish a desired task, which may be to feed electricity into the main distribution grid, to pump water from a well, to power a small calculator or one of many more possible uses of solar-generated electricity. The design of the system depends on the task it must perform and the location and other site conditions under which it must operate. This section will consider the components of a PV system, variations in design according to the purpose of the system, system sizing and aspects of system operation and maintenance.

System design

There are two main system configurations – stand-alone and grid-connected. As its name implies, the stand-alone PV system operates independently of any other power supply and it usually supplies electricity to a dedicated load or loads. It may include a storage facility (e.g. battery bank) to allow electricity to be provided during the night or at times of poor sunlight levels. Stand-alone systems are also often referred to as autonomous systems since their operation is independent of other power sources. By contrast, the grid-connected PV system operates in parallel with the conventional electricity distribution system. It can be used to feed electricity into the grid distribution system or to power loads which can also be fed from the grid.It is also possible to add one or more alternative power supplies (e.g. diesel generator, wind turbine) to the system to meet some of the load requirements. These systems are then known as 'hybrid' systems. Hybrid systems can be used in both stand-alone and grid-connected applications but are more common in the former because, provided the power supplies have been chosen to be complementary, they allow reduction of the storage requirement without increased loss of load probability. Figures below illustrate the schematic diagrams of the three main system types.

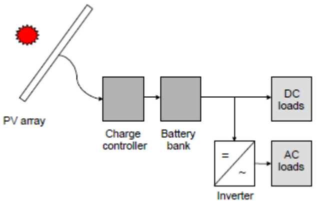


Fig. Schematic diagram of a stand-alone photovoltaic system.

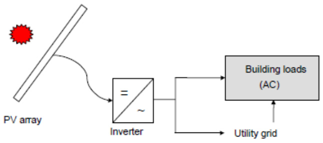


Fig. Schematic diagram of grid-connected photovoltaic system.

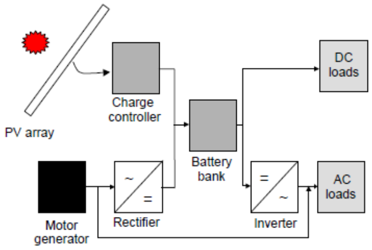


Fig. Schematic diagram of hybrid system incorporating a photovoltaic array and a motor generator (e.g. diesel or wind).

POWER MANAGEMENT

Power management is a feature of some electrical appliances, especially copiers, computers and computer peripherals such as monitors and printers, that turns off the power or switches the system to a low-power state when inactive. In computing this is known as PC power management and is built around a standard called ACPI. This supersedes APM. All recent (consumer) computers have ACPI support.

Motivation:

PC power management for computer systems is desired for many reasons, particularly:
Reduce overall energy consumption
Prolong battery life for portable and embedded systems
Reduce cooling requirements
Reduce noise.
Reduce operating costs for energy and cooling.
Lower power consumption also means lower heat dissipation, which increases system stability, and less energy use, which saves money and reduces the impact on the environment.

Processor level techniques:

The power management for microprocessors can be done over the whole processor, or in specific areas.
With dynamic voltage scaling and dynamic frequency scaling, the CPU core voltage, clock rate, or both, can be altered to decrease power consumption at the price of potentially lower performance. This is sometimes done in real time to optimize the power-performance tradeoff.

Examples:

AMD Cool'n'Quiet

AMD PowerNow! [1]

IBM EnergyScale [2]
Intel SpeedStep
Transmeta LongRun and LongRun2
VIA LongHaul (PowerSaver)
Additionally, processors can selectively power off internal circuitry (power gating). For example:
Newer Intel Core processors support ultra-fine power control over the functional units within the processors.
AMD CoolCore technology get more efficient performance by dynamically activating or turning off parts of the processor.[3]
Intel VRT technology split the chip into a 3.3V I/O section and a 2.9V core section. The lower core voltage reduces power consumption.

Power Management System helps to:

- Avoid Black-outs

In case of a lack of power, Load Shedding secures the electrical power to critical loads by switching off non-critical loads according to dynamic priority tables.Reduce Energy Costs / Peak Shaving.When all on-site power generation is maximized and the power demand still tends to exceed the contracted maximum electricity import, the system will automatically shed some of the low priority loads.Enhanced Operator Support..At sites where electricity is produced by several generators, the demands with respect to control activities by operators are much higher. Advanced functions such as intelligent alarm filtering, consistency analysis, operator guidance, and a well organized single-window interface support the operator and prevent incorrect interventions.
Achieve Stable Operation
The Power Control function shares the active and reactive power between the different generators and tie-lines in such a way that the working points of the machines are as far as possible away from the border of the individual PQ-capability diagrams so that the plant can withstand bigger disturbances.
Optimize Network Design Because the set points for the generators, turbines and transformers are calculated in such a way that no component will be overloaded and the electrical network can be used up to its limits, over-dimensioning of the network is no longer needed.

- Minimize Cabling and Engineering

All the signals and information which are available in protection/control relays, governor/excitation controllers and other microprocessor based equipment can be easily transmitted to the Industrial PMS via serial communication links. This avoids marshalling cubicles, interposing relays, cable ducts, spaghetti wiring, cabling engineering and provides extra functionality such as parameter setting/reading, stored events, disturbance data analysis and a single window to all electrical related data.

MODELLING OF CASE STUDY:

SYSTEM DESCRIPTION

A. *Structure of Grid-Connected Hybrid Power System*

The system consists of a PV-FC hybrid source with the main grid connecting to loads at the PCC as shown in Fig. 1. The photovoltaic and the PEMFC are modeled as nonlinear voltage sources. These sources are connected to dc–dc converters which are coupled at the dc side of a dc/ac inverter. The dc/dc connected to the PV array works as an MPPT controller. Many MPPT algorithms have been proposed in the literature, such as incremental conductance (INC), constant voltage (CV), and perturbation and observation (P&O). The P&O method has been widely used because of its simple feedback structure and fewer measured parameters. The P&O algorithm with power feedback control is shown in Fig. 2. As PV voltage and current are determined, the power is calculated. At the maximum power point, the derivative (dP/dV) is equal to zero. The maximum power point can be achieved by changing the reference voltage by the amount of ΔV_{ref}.

B. *PV Array Model*

The mathematical model can be expressed as

$$I = I_{\text{ph}} - I_{\text{sat}} \left\{ \exp\left[\frac{q}{AKT}(V + IR_s)\right] - 1 \right\}. \quad (1)$$

Equation (1) shows that the output characteristic of a solar cell is nonlinear and vitally affected by solar radiation, temperature, and load condition. Photocurrent I_{ph} is directly proportional to solar radiation G_{a}

$$I_{\text{ph}}(G_a) = I_{\text{sc}} \frac{G_a}{G_{\text{as}}}. \quad (2)$$

The short-circuit current of solar cell I_{sc} depends linearly on cell temperature

$$I_{\text{sc}}(T) = I_{\text{scs}}[1 + \Delta I_{\text{sc}}(T - T_s)]. \quad (3)$$

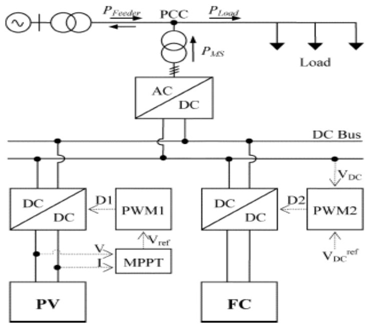


Fig. 1. Grid-connected PV-FC hybrid system.

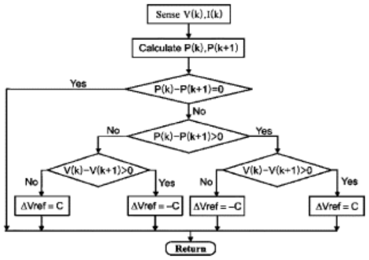


Fig. 2. P&O MPPT algorithm.

Thus, I_{ph} depends on solar irradiance and cell temperature I_{sat} also depends on solar irradiation and cell temperature and can be mathematically expressed as follows:

$$I_{\text{sat}}(G_a, T) = \frac{I_{\text{ph}}(G_a, T)}{e^{\left(\frac{V_{\text{oc}}(T)}{V_t(T)}\right)} - 1}. \quad (5)$$

C. *PEMFC Model*

The PEMFC steady-state feature of a PEMFC source is assessed by means of a polarization curve, which shows the nonlinear relationship between the voltage and current density. The PEMFC output voltage is as follows:

$$V_{\text{out}} = E_{\text{Nerst}} - V_{\text{act}} - V_{\text{ohm}} - V_{\text{conc}} \quad (6)$$

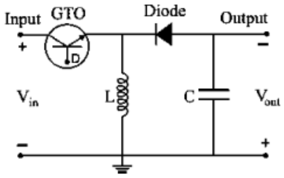


Fig. 3. Buck-boost topology.

Where E_{Nerst} is the "thermodynamic potential" of Nerst, which represents the reversible (or open-circuit) voltage of the fuel cell. Activation voltage drop V_{act} is given in the Tafel equation as

$$V_{\text{act}} = T[a + b\ln(I)] \quad (7)$$

where are the constant terms in the Tafel equation (in volts per Kelvin)

The overall ohmic voltage drop V_{ohm} can be expressed as

$$V_{\text{ohm}} = IR_{\text{ohm}}. \quad (8)$$

The ohmic resistance R_{ohm} of PEMFC consists of the resistance of the polymer membrane and electrodes, and the resistances of the electrodes.

The concentration voltage drop V_{conc} is expressed as

$$V_{\text{conc}} = -\frac{RT}{zF} ln\left(1 - \frac{I}{I_{\text{limit}}}\right). \quad (9)$$

D. *MPPT Control*

Many MPPT algorithms have been proposed in the literature, such as incremental conductance (INC), constant voltage (CV), and perturbation and observation (P&O). The two algorithms often used to achieve maximum power point tracking are the P&O and INC methods. The INC method offers good performance under rapidly changing atmospheric conditions. However, four sensors are required to perform the computations. If the sensors require more conversion time, then the MPPT process will take longer to track the maximum power point. During tracking time, the PV output is less than its maximum power. This means that the longer the conversion time is, the larger amount of power loss will be on the contrary, if the execution speed of the P&O method increases, then the system loss will decrease. Moreover, this method only requires two sensors, which results in a reduction of hardware requirements and cost. Therefore, the P&O method is used to control the MPPT process. In order to achieve maximum power, two different applied control methods that are often chosen are voltage-feedback control and power-feedback control. Voltage-feedback control uses the solar-array terminal voltage to control and keep the array operating near its maximum power point by regulating the array's voltage and matching the voltage of the array to a desired voltage. The drawback of the voltage-feedback control is its neglect of the effect of irradiation and cell temperature. Therefore, the power-feedback control is used to achieve maximum power.

The P&O MPPT algorithm with a power-feedback control is shown in Fig. 2. As PV voltage and current are determined, the power is calculated. At the maximum power point, the derivative ((dP/dV)) is equal to zero. The maximum power point can be achieved by changing the reference voltage by the amount of ΔV_{ref}.

In order to implement the MPPT algorithm, a buck-boost dc/dc converter is used as depicted in Fig. 3. The parameters L and C in the buck-boost converter must satisfy the following conditions:

$$L > \frac{(1-D)^2 R}{2f} \quad ; \quad C > \frac{D}{Rf(\Delta V/V_{\text{out}})}. \qquad (10)$$

The buck-boost converter consists of one switching device (GTO) that enables it to turn on and off depending on the applied gate signal D. The gate signal for the GTO can be obtained by comparing the saw tooth waveform with the control voltage.

The change of the reference voltage ΔV_{ref} obtained by MPPT algorithm becomes the input of the pulse width modulation (PWM). The PWM generates a gate signal to control the buck-boost converter and, thus, maximum power is tracked and delivered to the ac side via a dc/ac inverter.

CONTROL OF THE HYBRID SYSTEM

The control modes in the microgrid include unit power control, feeder flow control, and mixed control mode. The two control modes were first proposed by Lasserter. In the UPC mode, the DGs (the hybrid source in this system) regulate the voltage magnitude at the connection point and the power that source is injecting. In this mode if a load increases anywhere in the microgrid, the extra power comes from the grid, since the hybrid source regulates to a constant power. In the FFC mode, the DGs regulate the voltage magnitude at the connection point and the power that is flowing in the feeder at connection point. With this control mode, extra load demands are picked up by the DGs, which maintain a constant load from the utility viewpoint.. In the mixed control mode, the same DG could control either its output power or the feeder flow power. In other words, the mixed control mode is a coordination of the UPC mode and the FFC mode. Both of these concepts were considered. In this paper, a coordination of the UPC mode and the FFC mode was investigated to determine when each of the two control modes was applied and to determine a reference value for each mode. Moreover, in the hybrid system, the PV and PEMFC sources have their constraints. Therefore, the reference power must be set at an appropriate value so that the constraints of these sources are satisfied.

The proposed operation strategy presented in the next section is also based on the minimization of mode change. This proposed operating strategy will be able to improve performance of the system's operation and enhance system stability.

OPERATING STRATEGY OF THE HYBRID SYSTEM

As mentioned before, the purpose of the operating algorithm is to determine the control mode of the hybrid source and the reference value for each control mode so that the PV is able to work at maximum output power and the constraints $(P_{\text{FC}}^{\text{low}}, P_{\text{FC}}^{\text{up}}, \text{and } P_{F}^{\max})$ are fulfilled.

Once the constraints (and) are known, the control mode of the hybrid source (UPC mode and FFC mode) depends on load variations and the PV output. The control mode is decided by the algorithm shown in Fig. 7, Subsection B. In the UPC mode, the reference output power of the hybrid source depends on the PV output and the constraints of the FC output. The algorithm determining is presented in Subsection A and is depicted in Fig. 4.

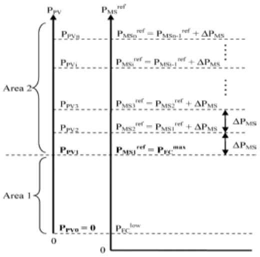


Fig. 4. Operation strategy of hybrid source in the UPC mode.

Operating Strategy for the Hybrid System in the UPC Mode

In this subsection, the presented algorithm determines the hybrid source works in the UPC mode. This algorithm allows the PV to work at its maximum power point, and the FC to work within its high efficiency band. In the UPC mode, the hybrid source $P^{\mathrm{ref}}_{\mathrm{MS}}$ regulates the output to the reference value. Then

$$P_{\mathrm{PV}} + P_{\mathrm{FC}} = P^{\mathrm{ref}}_{\mathrm{MS}}. \qquad (11)$$

Equation (11) shows that the variations of the PV output will be compensated for by the FC power and, thus, the total power will be regulated to the reference value.
However, the FC output must satisfy its constraints and, hence, $P^{\mathrm{ref}}_{\mathrm{MS}}$ must set at an appropriate value. Fig. 4 shows the operation strategy of the hybrid source in UPC mode to determine $P^{\mathrm{ref}}_{\mathrm{MS}}$. The algorithm includes two areas: Area 1 and Area 2.

In Area 1, P_{PV} is less than P_{PV1}, and then the reference Power $P^{\mathrm{ref}}_{\mathrm{MS1}}$ is set at $P^{\mathrm{up}}_{\mathrm{FC}}$ where

$$P_{\mathrm{PV1}} = P^{\mathrm{up}}_{\mathrm{FC}} - P^{\mathrm{low}}_{\mathrm{FC}} \qquad (12)$$
$$P^{\mathrm{ref}}_{\mathrm{MS1}} = P^{\mathrm{up}}_{\mathrm{FC}}. \qquad (13)$$

If PV output is zero, then (11) P_{FC} deduces to be equal to $P^{\mathrm{up}}_{\mathrm{FC}}$. If the PV output increases to P_{PV1}, then from (11) and (12), we obtain P_{FC} equal to $P^{\mathrm{low}}_{\mathrm{FC}}$. In other words, when the PV output varies from zero to P_{PV1}, the FC output will change from $P^{\mathrm{up}}_{\mathrm{FC}}$ to $P^{\mathrm{low}}_{\mathrm{FC}}$. As a result, the constraints for the FC output always reach Area 1. It is noted that the reference power of the hybrid source during the UPC mode is fixed at a constant $P^{\mathrm{up}}_{\mathrm{FC}}$. Area 2 is for the case in which PV output power is greater Than P_{PV1}. As examined earlier, when the PV output increases. To P_{PV1}, the FC output will decrease to its lower limit $P^{\mathrm{low}}_{\mathrm{FC}}$. If PV output keeps increasing, the FC output will decrease below its limit $P^{\mathrm{low}}_{\mathrm{FC}}$.

In this case, to operate the PV at its maximum power point and the FC within its limit, the reference power must be increased. As depicted in Fig. 4, if PV output is larger than P_{PV1}, the reference power will be increased by the amount of ΔP_{MS}, and we obtain

$$P^{\mathrm{ref}}_{\mathrm{MS2}} = P^{\mathrm{ref}}_{\mathrm{MS1}} + \Delta P_{\mathrm{MS}}. \qquad (14)$$

$$P^{\mathrm{ref}}_{\mathrm{MS}i} = P^{\mathrm{ref}}_{\mathrm{MS}i-1} + \Delta P_{\mathrm{MS}} \qquad (17)$$
$$P_{\mathrm{PV}i} = P_{\mathrm{PV}i-1} + \Delta P_{\mathrm{MS}}. \qquad (18)$$

Similarly, if P_{PV} is greater than P_{PV2}, the FC output becomes less than its lower limit and the reference power will be thus increased by the amount of ΔP_{MS}. In other words, the reference

power remains unchanged and equal to $P^{\mathrm{ref}}_{\mathrm{MS2}}$ if is less than P_{PV2} and greater than P_{PV1}.
where

$$P_{\mathrm{PV2}} = P_{\mathrm{PV1}} + \Delta P_{\mathrm{MS}} \qquad (15)$$

it is noted that ΔP_{MS} is limited so that with the new reference power, the FC output must be less than its upper limit $P^{\mathrm{up}}_{\mathrm{FC}}$. Then, we have $P_{\mathrm{PV}i}$ and $P_{\mathrm{PV}i-1}$

In general, if the PV output is between and , then we have

Equations (17) and (18) show the method of finding the reference power when the PV output is in Area 2. The relationship between $P^{\mathrm{ref}}_{\mathrm{MS}i}$ and $P_{\mathrm{PV}i}$ is obtained by using (12), (13), and
(18) in (17), and then

$$P^{\mathrm{ref}}_{\mathrm{MS}i} = P_{\mathrm{PV}i} + P^{\mathrm{min}}_{\mathrm{FC}}, \quad i = 2, 3, 4 \ldots \qquad (19)$$

The determination of $P_{\mathrm{MS}}^{\mathrm{ref}}$ in Area 1 and Area 2 can be generalized by starting the index from 1. Therefore, if the PV output

$$P_{\mathrm{PV}i-1} \leq P_{\mathrm{PV}} \leq P_{\mathrm{PV}i}, \quad i = 1,2,3\ldots$$

then we have

$$P_{\mathrm{MS}i}^{\mathrm{ref}} = P_{\mathrm{PV}i} + P_{\mathrm{FC}}^{\mathrm{min}}, \quad i = 1,2,3\ldots \tag{20}$$

$$P_{\mathrm{PV}i} = P_{\mathrm{PV}i-1} + \Delta P_{\mathrm{MS}}, \quad i = 2,3,4\ldots \tag{21}$$

it is noted that $i = 1, P_{\mathrm{PV}1}$ when is given in (12), and

$$P_{\mathrm{PV}i-1} = P_{\mathrm{PV}0} = 0. \tag{22}$$

In brief, the reference power of the hybrid source is determined according to the PV output power. If the PV output is in Area 1, the reference power will always be constant and set at $P_{\mathrm{FC}}^{\mathrm{up}}$. Otherwise, the reference value will be changed by the amount of ΔP_{MS}, according to the change of PV power.

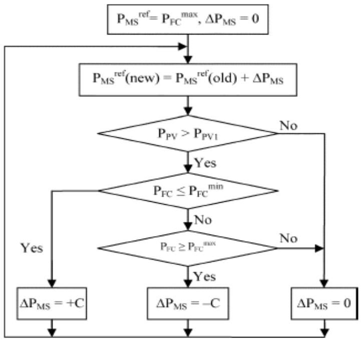


Fig. 5. Control algorithm diagram in the UPC mode ($P_{\mathrm{MS}}^{\mathrm{ref}}$ automatically changing).

The reference power of the hybrid source in Area 1 and Area 2 is determined by (20) and (21). , and are shown in (22), (12), and (16), respectively. Fig. 5. shows the control algorithm diagram for determining the reference power automatically.

$$\Delta P_{\mathrm{MS}} \leq P_{\mathrm{FC}}^{\mathrm{up}} - P_{\mathrm{FC}}^{\mathrm{low}}. \tag{16}$$

The constant must satisfy (16). If increases the number of change of will decrease and thus the performance of system operation will be improved. However, C should be small enough so that the frequency does not change over its limits 5%). In order to improve the performance of the algorithm, a hysteresis is included in the simulation model. The hysteresis is used to prevent oscillation of the setting value of the hybrid system reference power . At the boundary of change in , the reference value will be changed continuously due to the oscillations in PV maximum power tracking. To avoid the oscillations around the boundary, a hysteresis is included and its control scheme to control is depicted in Fig.6.

B. Overall Operating Strategy *for the Grid-Connected Hybrid System*

It is well known that in the microgrid, each DG as well as the hybrid source has two control modes: 1) the UPC mode and 2) the FFC mode. In the aforementioned subsection, a method to determine in the UPC mode is proposed. In this subsection, an operating strategy is presented to coordinate the two control modes.

The purpose of the algorithm is to decide when each control mode is applied and to determine the reference value of the feeder flow when the FFC mode is used. This operating strategy must enable the PV to work at its maximum power point, FC output, and feeder flow to satisfy their constraints. If the hybrid source works in the UPC mode, the hybrid output is regulated to a reference value and the variations in load are matched by feeder power. With the reference power proposed in Subsection A, the constraints of FC and PV are always satisfied. Therefore, only the constraint of feeder flow is considered. On the other hand, when the hybrid works in the FFC mode, the feeder flow is controlled to a reference value

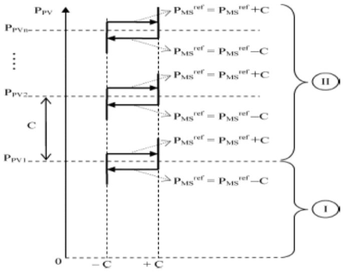


Fig. 6. Hysteresis control scheme for $P_{\mathrm{MS}}^{\mathrm{ref}}$ control.

And, thus, the hybrid source will compensate for the load variations. In this case, all constraints must be considered in the operating algorithm. Based on those analyses, the operating strategy of the system is proposed as demonstrated in Fig. 7. The operation algorithm in Fig. 7 involves two areas (Area I and Area II) and the control mode depends on the load power. If load is in Area I, the UPC mode is selected. Otherwise, the FFC mode is applied with respect to Area II. In the UPC area, the hybrid source output.

If the load is lower than , the redundant power will be transmitted to the main grid. Otherwise, the main grid will send power to the load side to match load demand. When load increases, the feeder flow will increase correspondingly. If feeder flow increases to its maximum , then the feeder flow cannot meet load demand if the load keeps increasing. In order to compensate for the load demand, the control mode must be changed to FFC with respect to Area II. Thus, the boundary between Area I and Area II is

$$P_{\text{Load1}} = P_{\text{Feeder}}^{\max} + P_{\text{MS}}^{\text{ref}}. \tag{23}$$

When the mode changes to FFC, the feeder flow reference must be determined. In order for the system operation to be seamless, the feeder flow should be unchanged during control mode transition. Accordingly, when the feeder flow reference is set at , then we have

$$P_{\text{Feeder}}^{\text{ref}} = P_{\text{Feeder}}^{\max}. \tag{24}$$

In the FFC area, the variation in load is matched by the hybrid source. In other words, the changes in load and PV output are compensated for by PEMFC power. If the FC output increases to its upper limit and the load is higher than the total generating power, then load shedding will occur. The limit that load shedding will be reached is

$$P_{\text{Load2}} = P_{\text{FC}}^{\text{up}} + P_{\text{Feeder}}^{\max} + P_{\text{PV}}. \tag{25}$$

Equation (25) shows that is minimal when PV output is at 0 kW. Then

$$P_{\text{Load2}}^{\min} = P_{\text{FC}}^{\text{up}} + P_{\text{Feeder}}^{\max}. \tag{26}$$

Equation (26) means that if load demand is less than , load shedding will never occur.

load shedding is ensured not to occur. However, in severe conditions, FC should mobilize its availability, to supply the load. Thus, the load can be higher and the largest load is

$$P_{\text{Load}}^{\max} = P_{\text{FC}}^{\max} + P_{\text{Feeder}}^{\max}. \tag{27}$$

If FC power and load demand satisfy (27), load shedding will never occur. Accordingly, based on load forecast, the installed power of FC can be determined by following (27) to avoid load shedding. Corresponding to the FC installed power, the width of Area II is calculated as follows:

$$P_{\text{Area-II}} = P_{\text{FC}}^{\max} - P_{\text{FC}}^{\text{up}}. \tag{28}$$

In order for the system to work more stably, the number of mode changes should be decreased. As seen in Fig. 7, the limit changing the mode from UPC to FFC is , which is calculated in (23). Equation (23) shows that depends on $P_{\text{Feeder}}^{\max}$ and $P_{\text{MS}}^{\text{ref}}$. $P_{\text{Feeder}}^{\max}$ is a constant.Thus depends on Fig. 4 shows that in Area 2 $P_{\text{MS}}^{\text{ref}}$ depends on . Therefore, to decrease the number of mode changes, $P_{\text{MS}}^{\text{ref}}$ changes must be reduced. Thus, ΔP_{MS} must be increased. However ΔP_{MS} must satisfy condition (16) and, thus, the minimized number of mode change is reached when ΔP_{MS} is maximized

TABLE I
SYSTEM PARAMETERS

Parameter	Value	Unit
P_{FC}^{low}	0.01	MW
P_{FC}^{up}	0.07	MW
P_{Feeder}^{max}	0.01	MW
ΔP_{MS}	0.03	MW

$$\Delta P_{\text{MS}}^{\max} = P_{\text{FC}}^{\text{up}} - P_{\text{FC}}^{\text{low}}. \tag{29}$$

In summary, in a light-load condition, the hybrid source works in UPC mode, the hybrid source regulates output power to the reference value $P_{\text{MS}}^{\text{ref}}$, and the main grid compensates for load variations. $P_{\text{MS}}^{\text{ref}}$ is determined by the algorithm shown in Fig. 4 and, thus, the PV always works at its maximum power point and the PEMFC always works within the high efficiency band $(P_{\text{FC}}^{\text{low}} \div P_{\text{FC}}^{\text{up}})$. In heavy load conditions, the control mode changes to FFC, and the variation of load will be matched by the hybrid source. In this mode, PV still works with the MPPT control, and PEMFC operates within its efficiency band until load increases to a very high point. Hence, FC only works outside the high efficiency band $(P_{\text{FC}}^{\text{up}} \div P_{\text{FC}}^{\max})$ in severe conditions. With an installed power of FC and load demand satisfying (27), load shedding will not occur. Besides, to reduce the number of mode changes, must be increased and, hence, the number of mode changes is minimized when is maximized, as shown in (29). In addition, in order for system operation to be seamless, the reference value of feeder flow must be set at P^{max}_{Feeder} .

MATLAB DESIGN OF CASE STUDY AND RESULTS:

Case I: Fig. 8a

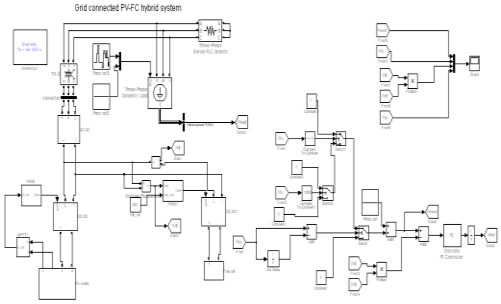


Fig. Grid connected PV-FC hybrid system

Case II: Fig. 8b

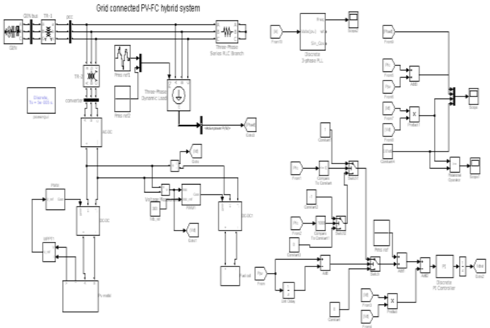


Fig. Grid connected PV-FC hybrid system

Case III: Fig. 9a

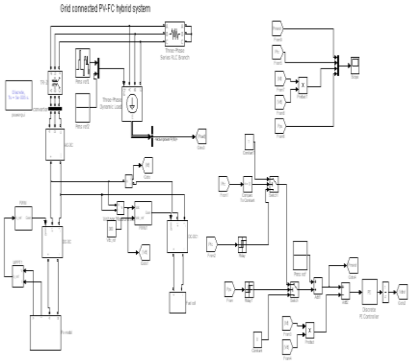


Fig. Grid connected PV-FC hybrid system

Case IV: Fig. 9b

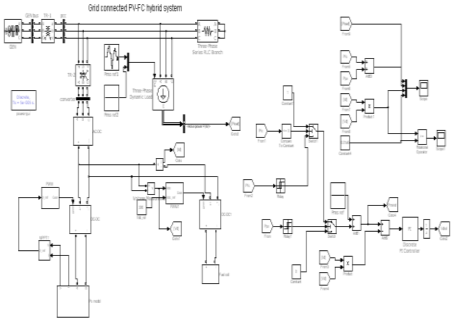


Fig. Grid connected PV-FC hybrid system

CONCLUSION:

This paper has presented an available method to operate a hybrid grid-connected system. The hybrid system, composed of a PV array and PEMFC, was considered. The operating strategy of the system is based on the UPC mode and FFC mode. The purposes of the proposed operating strategy presented in this paper are to determine the control mode, to minimize the number of mode changes, to operate PV at the maximum power point, and to operate the FC output in its high-efficiency performance band.

The main operating strategy, shown in Fig. 7, is to specify the control mode; the algorithm shown in Fig. 4 is to determine P^{ref}_{MS} in the UPC mode. With the operating algorithm, PV always operates at maximum output power, PEMFC operates within the high-efficiency range $(P_{\mathrm{FC}}^{\mathrm{low}} \div P_{\mathrm{FC}}^{\mathrm{up}})$, and feeder power flow is always less than its maximum value $(P_{\mathrm{Feeder}}^{\max})$. The change of the operating mode depends on the current load demand, the PV output, and the constraints of PEMFC and feeder power. With the proposed operating algorithm, the system works flexibly, exploiting maximum solar energy; PEMFC works within a high-efficiency band and, hence, improves the performance of the system's operation. The system can maximize the generated power when load is heavy and minimizes the load shedding area. When load is light, the UPC mode is selected and, thus, the hybrid source works more stably.

The changes in operating mode only occur when the load demand is at the boundary of mode change (P_{Load1}); otherwise, the operating mode is either UPC mode or FFC mode. Besides, the variation of hybrid source reference power $P_{\mathrm{MS}}^{\mathrm{ref}}$ is eliminated by means of hysteresis. In addition, the number of mode changes is reduced. As a consequence, the system works more stably due to the minimization of mode changes and reference value variation. In brief, the proposed operating algorithm is a simplified and flexible method to operate a hybrid source in a grid-connected microgrid. It can improve the performance of the system's operation; the system works more stably while maximizing the PV output power. For further research, the operating algorithm, taking the operation of the battery into account to enhance operation performance of the system, will be considered. Moreover, the application of the operating algorithm to a microgrid with multiple feeders and DGs will also be studied in detail.

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