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A guide to a range of electrical energy storage devices with an assessment of fuel cells

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It is always desirable to de-couple the generation and the use of electrical energy, for example, to power mobile devices, to provide remote energy power support, or to simply spread electricity demand evenly over the daily cycle. This is achieved by using some form of an electrical energy storage system. Nowadays there are many such systems available each with its own cost, efficiency, and suitability for different applications with developments continuing all the time. This survey will aim to summarize the available electrical Energy Storage Devices (ESD), assessing their general advantages and disadvantages, reviewing their main applications available focusing on the storage of energy for electrical purposes. Finally a detailed survey is given for fuel cells to be used in energy storage as well as in more clean and efficient energy production.

من المفضل دائما إيجاد وسيلة للتنسيق الأمثل بين الطاقة المولدة والطاقة المستخدمة ، مثلا كما هو الحال في أجهزة الطاقة المتحركة التي تساعد في تغطية الحاجة الكهربية المؤقتة أو في حالة توزيع الحاجة الكهربية بالتساوى على مدار اليوم. في يومنا هذا هناك العديد من هذه الوسائل متوفرة ولكل منها سعرها الخاص وكفاءتها ومناسبتها للتطبيقات المختلفة مع التطور المستمر لها طوال الوقت . هذا البحث يلخص أولا جميع أجهزة تخزين الطاقة المتوفرة مع التقييم لمميزات وعيوب كل جهاز، مع عرض للتطبيقات المتوفرة له. ثم يتطرق البحث إلى دراسة تفصيلية لخلايا الوقود كواحدة من أجهزة التخزين الكهربي مع كونها أيضا واحدة من أكفأ وسائل التوليد النظيفة في مجال الطاقة المتجددة.

Keywords: Energy storage devices, Remote energy power support, Fuel cells, Renewable energy

1. Introduction

Electrical power is traditionally generated centrally then transmitted and distributed by an electricity grid. This was for reasons of convenience depending on where the fuel is available. Electricity from renewable energy sources can be also used this way, but it can be also generated and used locally as the resource. This is an advantage when transmission grid is weak or don't exist as in an island. This can lead to the use of Energy Storage Devices (ESD) in association with embedded renewable energy sources to store energy when produced (by wind, solar, or tidal) to be used whenever required. The choice of the suitable ESD depends on the many factors; this paper will review all the possible ESD and the choice of the most appropriate one for the different situations.

As the energy sector is responsible for a significant proportion of the emissions of the most common air pollutants, trends towards the use of cleaner and more efficient generation systems appear. Fuel cells present low operational emissions as compared to other technologies based on fossil fuels. They can also provide major environmental, energy, and economic benefits, that's why we will discuss fuel cells here in more detail.

2. Review of key applications

Electrical energy storage [1] can be used for many tasks, ranging from small scale (rechargeable power supplies for mobile phones) to very large scale (utility supply load levelling). This section will give a brief look at the key uses of ESDs which are divided into "Power" applications (those associated with large amounts of electricity either at the generation plant or used by customer), and "Non-power" applications [1-3].

2.1. Power applications

2.1.1. Generator power applications

1. Generator load levelling: Due to the difference in demand for electricity between day and night, summer and winter; only those plants with low operating prices and less flexibility are used during off-peaks. This set up a price difference between day and night, and between summer and winter electricity. ESDs can be used to take an advantage of these differences, by charging up during the low cost period and discharging during the high cost period. An example for this in the UK is the "Dinorwig Pumped Hydro Station".
2. Deferral of constructing new plan. When the available generating capacity gets close to the peak demand of the system, an ESD can be installed to store the existing under-utilised night-time (or winter-time) capacity of the existing plants, to cover the peak periods, thus increasing the network flexibility.
3. Spinning and standing reserve. This can be produced by installing to the system an ESD that is partly charged so that it can easily accept surplus electricity from the network, or provide extra electricity when there is a deficit.
4. Reduction in transmission congestion. To avoid overstressing a bottleneck (nodes that link large generation to large demand), the operator might be forced to take supply from more expensive but better positioned plants. The existence of an ESD beyond the bottleneck(i.e., closer to demand) enables power to be transmitted past the node during an off-peak time and held until required, increasing generation flexibility and reducing the overall cost.
5. Generator black start. The ESD options which can start without an electricity source, can be used to cover the period between blackout (catastrophic failure on the network so that all power is lost) and getting the system up and running again, in spite of using the relatively expensive diesel turbines currently used.
6. Enhancement of renewable energy. Renewable energy is typically installed at the embedded level (i.e. not to the grid but direct to the users). As customers usually want the supply to be as flexible as possible and as the main renewable energy sources (wind, solar, and tidal power) doesn't meet this very well, thus the attachment of an ESD to a renewable energy source can guarantee a more flexible and predictable supply.
7. Storage for CHP systems. As Constant Heat and Power systems (CHP) systems generate heat and power at the same time, this implies that there will be periods of surplus of heat or power generated depending on the primary use of the system. Thus ESDs present an opportunity to improve the attractiveness of CHP projects as the installation of a thermal ESD and/or an electrical ESD de-couples the times at which the heat and power are used.
8. Power quality support. To avoid or minimize interruptions in the generation facilities, ESDs can be used to remove particularly the short-term fluctuations from their supply. The attractiveness of such an investment depends on any penalties imposed on generating units that fail to provide a quality supply.

2.1.2. User power applications

1. Customer-demand peak shaving. This is the user equivalent of load levelling. As the generating company can store some of its cheap power to sell during day, also a user may purchase cheaper nighttime power to reduce his use of more expensive daytime electricity.
2. Uninterruptible Power Supply (UPS). The basic mandate of an UPS system is that it should come into operation automatically, with negligible delay and transients, immediately following the failure or fluctuation of the utility supply to provide power for the load until normal supply is restored. A typical UPS includes an ESD, a fast acting switching system, and possibly a back-up generator to provide longer running alternative power.
3. Storage for remote users. Remote power users may suffer a less reliable or stable service. An ESD can be used to protect the power supply and possibly provide UPS services to enhance the quality of power received.

2.2. Non-power applications

1. Vehicle regenerative braking. In spite of wasting the kinetic energy when a vehicle brakes and burning more fuel to accelerate

again, a more efficient system would be to transfer the kinetic energy of the fast vehicle to a short term ESD and then use that stored energy when needed to accelerate again.
2. Mobile and small-scale power supply. Lots of portable devices (mobile phones, pagers, portable computers, personal organisers, watches, outdoor refrigeration, and others) require independent power supplies. The traditional sources have been the primary and secondary battery and hydrocarbon fuels. Some companies are looking for the possibility of using other ESDs and in particular fuel cells to provide this power.

3. A Survey on ESDs and their applications

Electrical energy storage devices are used to decouple the generation and the use of electricity. In the following we will review different technologies for accomplishing these using mechanical, electromagnetic, or electrochemical techniques. Some of the proposed devices have been around for centuries whereas others are recent developments. We will stress here on the fuel cells, as they are the point of interest.

3.1. Mechanical energy storage devices

Electrical energy can be produced from mechanical energy either the Kinetic Energy (K.E) like the flywheel or the gravitational or distortional Potential Energy (P.E) by the use of a dynamo.
1. Flywheel energy storage. The idea is to charge a flywheel to very high rotational speed then use the electrical energy generated during spin down as the power source. To maximize the energy stored in a flywheel one should maximize its mass, radius, and its angular velocity. The main factor in flywheel technology has been the development of stronger composite materials. The most powerful flywheel is from the University of Texas (3MW) for 2.5 minutes.
2. Distortional energy storage. It takes many forms like that in spring, elastic, or compressed air. Compressed Air Energy Storage (CAES) in which power is used to compress air in an underground rock or salt caverns to avoid leakage, then when required the air is released either through a turbine to generate electricity or into combustion chamber with fuel. The efficiency of such systems depends on the efficiency of compressor and turbine. The limitations of its use are the need of suitable underground facility and expertise in subsurface geology. Some of the available CAES are:
1. The Huntorf CAES in Germany (290MW) 10 years old, 90% availability, 99% reliability.
2. McIntosh CAES (1991) Alabama (110MW).
3. Sesta CAES in Italy (25MW).
4. Japan (35MW).
5. Israel (300 MW).
6. Russia (1050MW).

3. Gravitational Energy Storage. This is as in the pendulum and pump storage. It has been used for ages in clocks. In "Pumped Hydro" the energy is stored by pumping water up-hill, and when needed the water is allowed to fall down through turbines which generate electricity. Efficiency here depends on the efficiency of the pump and turbine. There are 290 plants worldwide, one of them is: The *Dinorwig Plant in Wales, UK. It is one of the* best-known pumped storage plants in the world (1.8GW in less than 16 seconds).

3.2. Electromagnetic energy storage devices

1. Capacitor energy storage. The energy stored in capacitor C farads when subjected to voltage V volts is given by:

$$E = \frac{1}{2} CV^2$$

In order to increase the amount of energy stored for a given voltage the capacitance must be increased, where $C = A\varepsilon/d$.

Notice that capacitors are classified by their dielectric (air, mica, paper, plastic, ceramic, and electrolytic). The maximum energy storage is obtained by dielectrics that have highest breakdown voltages.
2. Super-conducting Magnetic Energy Storage (SMES): This is one of the newest storage options. The energy stored in a coil of inductance L when a current I flows in it is given by:

$$E = \frac{1}{2} LI^2$$

Energy is stored in the magnetic field generated from the flow of current in the wire. The coil is made of a super-conducting wire so that there are no resistive losses. This system is 100% efficient; the only energy loss is for running the refrigeration unit to cool the coil down to its super-conducting temperature. At present SMES are proposed on several scales with specific design tasks in mind. Because of its high cost, it is necessary for the units to be optimized to the specific application being considered. Some of the running projects are: Finland (32KW), Germany (15MW, 210KW, 20KW, and 4.14MW), and Israel (23KW).

3.3. Electrochemical energy storage devices

Energy is stored here as chemical potential. The first invented device was the battery in which a chemical reaction takes place within constitutes of the cell to generate electricity. After that the fuel cells were conceived in which hydrogen and water in a cell generates electricity and water which is decoupled again in the storage step. Finally, a recent development is the Regenerative fuel cell, which uses chemicals other than hydrogen and water to achieve the same effect as conventional fuel cells.

1. Battery energy storage. Battery is a collection of several cells. Batteries are either primary (they produce energy as they are discharged but cannot be recharged), or secondary batteries (their process is reversible). The majority of ESDs are secondary BES.

2. Fuel cell energy storage. In 1839 Sir William Grove invented its concept that reversing the electrolysis of water (i.e. reacting hydrogen and oxygen) generates electricity. In 1889 Ludwig Mond and Charles Langer attempted to build the first fuel cell using air and industrial coal gas. In 1950 Francis T. Bacon demonstrates the first practical working fuel cell.

Extensive further development occurred in the 1960s, as NASA choose fuel cells over the riskier nuclear power, heavier batteries and more expensive solar energy for their Gemini and Apollo missions (nowadays fuel cells still supply electric power and drinking water to space shuttles). Today, numerous companies are developing various types of fuel cells for different markets. Lately, with the growing interesting environmentally friendly technology, car companies work towards commercial fuel cell vehicles [7].

3.4. Theory

In principle a fuel cell operates like a battery [8, 9, and 10]. Unlike a battery, it does not run down or require recharging. It will produce energy in the form of electricity and heat as long as fuel is supplied. A fuel cell consists of two porous electrodes sandwiched around an electrolyte. Oxygen (or air) passes over the cathode and hydrogen gets oxidised over the anode encouraged by a catalyst, generating electricity, water and heat. The voltage measured across the anode and cathode of a single fuel cell ranges between 0.9V and 0.5V. The fuel cell stack is made up of a number of modules, which are in turn made up of a number of fuel-cell electrodes electrically connected in series or in parallel. Although the majority of fuel cells use hydrogen directly as fuel, some fuel cells work off methane, and few use liquid fuels as methanol and even treated gas from landfill or sewage sites. Energy can be also supplied by biomass, wind, solar power or other renewable sources.

As fuel cell works by converting the chemical energy of a fuel into electrical energy. The chief benefit over burning the fuel is that the electrical energy is generated without wasted heat generation, thus increasing the electrical energy per kg of fuel.

In order for the fuel cell to be an ESD, it must be combined with some other means of converting electrical energy into chemical energy to make a regenerative fuel cell (RFC). In this case the fuel used would be hydrogen as we can regenerate hydrogen from the resulting water by electrolysis. The hydrogen and oxygen resulting from the split of water may be stored without losses for an indefinite period of time, when required the gas is supplied to the fuel cell's electrodes generating a potential difference and current flows. To construct a RFC three systems are required: the fuel cell, the electrolysis system and some means of storing the hydrogen.

The main classes of fuel cells (identified by the electrolyte used) are:
1. Alkaline Fuel Cell (AFC). Still the cell used in space shuttle. It can achieve power generating efficiency up to 70%. Alkaline Potassium Hydroxide is the electrolyte.
2. Polymer Electrolyte Membrane (PEM): It has a high power density, low operating temperature and can vary its output quickly to meet shifts in power demands. It is used in portable devices, cars, and for some home trials as domestic heating requirements. This is the most actively researched as of its commercial potential.
3. Phosphoric Acid Fuel Cell (PAFC). This is the most commercially developed to date. They have been used in larger vehicles like buses, and their main application is as a stationary power supply of 200kW for hospitals, hotels and office buildings. Their efficiency is about 40 %, which may be increased by using the waste heat in cogeneration.
4. Molten Carbonate (MCFC) and Solid Oxide (SOFC). These 2 fuel cells operate at sufficiently high temperatures for organic fuels such as methane or natural gas to be internally reformed. They are unlikely to be ESD, as hydrogen can't be used at their high temperatures.

The electrolysis unit for the production of hydrogen can be high temperature electrolyser (that uses the waste heat for breaking water), traditional low-pressure electrolyser, and the relatively new PEM electrolyser (which has been used in the past to produce life-support oxygen in submarines and space stations). The hydrogen storage can be obtained by compressing the gas, converting it to liquid, or binding it to solids.

From the above it can be seen that many combinations of fuel cell, electrolyser, and hydrogen storage medium are possible. It is necessary to pack all three components in a compact system to form an ESD. If the fuel cell and the electrolyser roles can be performed reversibly by one piece of equipment we get a so-called Utilized Regenerative Fuel Cell (URFC). After selecting the fuel cell type, usually we design a stack of them to increase the generated DC voltage to 1.23V.

On 1999 the National Power's technology section Innogy, announced the development of a new ESD technology "Regenesys". It is analogous to a traditional fuel cell, except that it uses electrolytic solutions rather than hydrogen and oxygen to store the energy. They say it can support 5 – 500 MW for times of few seconds to 12 hours.

3.5. The fuel cell system

The fuel-cell system consists of the fuel cell modules combined in stacks, the peripheral equipment to support the principal fluid loops, the electronic power interface between the fuel cell and the electrical load, and the system controller. The electrical load normally includes a buffer battery to protect the fuel cell from excessive power surges.

4. Environmental benefits of fuel cells

In selecting an ESD it may be useful to choose a device with a low environmental impact. Four parameters can characterise these impacts; the materials used, emissions, safety, and physical impact. Also trends towards clearer generation systems in the power market, as well as in automobiles are increasing to decrease the pollution levels. Since fuel cells can be used in generation, transportation and storage, and as they rely on chemistry and not combustion making their emissions much smaller than that from the cleanest fuel combustion process; thus fuel cells can help in reducing the emissions. Fuel cells running on hydrogen from a renewable source produce only water vapour and no CO_2.

The US department of energy projects found out that if 10% of automobiles nationwide are powered by fuel cells, the regulated air pollutes would be cut by 1 million tons/year and 60 million tons of CO_2 could be eliminated. Regarding the safety of hydrogen storage, safety tests performed by Ford Motor Company for the US Department of Energy proved that it is safer to store hydrogen than gasoline.

5. An assessment of fuel cells

Fuel cells are a technology [4- 6] that can:

- Contribute substantially to a global low carbon dioxide economy, which means there will be neither atmospheric nor ground pollution.
- Improve urban air quality and global warming, and has no noise pollution.
- Make an important contribution to energy security concerns by allowing a wider choice of fuels and hence enhance the prospects for international stability.
- Provide essential intermediate and final components of any future hydrogen economy.
- As a new and innovative technology, fuel cells can provide attractive solutions to complex problems.
- Store electrical energy when no energy is needed (unlike batteries which need to be recharged), thus there is no power loss when system is switched off.
- Has a good efficiency better than that of heat engines.
- Be made in a huge range of sizes, ranging from those producing quite small amounts of electric power for devices such as portable computers or radio transmitters, right up to very high powers for electric power stations.
- Address a highly reliable fuel cell that establishes a number of parallel paths in every aspect of fuel cell so that individual path may go out of service, but substantial capacity is available all the time.
- Provide promising automotive applications as we can use motors which are not too high in voltage, and even if the cost of the car is more expensive this is acceptable taking into account the environmental considerations. However, car engines could be built for about the same price as an internal combustion engine (as noted by General Motors and Ford studies).
- Supply some applications which require low voltage. It can supply some buildings, like broadcasting buildings, banks, hospitals, or research laboratories need constant power supply for some typical device like security system or fire alarm system and it will be catastrophic to have a cut off.
- Be used in the electronic domain as there is no need to have a high voltage supply. It can be used as an emergency power supply or even a stand alone power for the electronic devices of uninterruptible power supply (UPS) buildings or the high security buildings where the cost is less important as investing money for security or reliability worth it.
- Be promising in some deserted region of the world, in order to increase the development of this region by bringing there the technology and the skills to handle it, and to produce a clean energy and environmental considerations.

Fuel cells are still a young technology. Many technical and engineering challenges remain; scientists and developers are hard at work on them. The main drawbacks are:

- The cost: the price of a fuel cell is high due to the use of expensive and/or very specific materials.
- The low output voltage for the power it gives limits its use for supplying most of the home appliances as well as the industrial applications in which the generators require a high starting current. This low voltage needs power electronics devices to be added to the overall system as an interface between the fuel cell and the load thus complicating its design.
- The slowness of reaction which limits the rate of rise of the current making it unable to meet fast-variation loads.

6. Use of fuel cells in power industry

One of the major benefits of fuel cells is the ability to provide power and heat at scales ranging from local networks to micro-grids and individual buildings/dwellings, and in locations not currently accessible.

Fuel cells also offer improvements in energy efficiency and reductions in emissions. Fuel cells are important also in UPS systems to minimize or eliminate the inconvenience caused by power supply quality issues.

The ability of fuel cells to operate on fuels ranging from fossil fuels through biomass based fuels to renewable means that they can support all steps in transition to hydrogen economy. They are the best way to maintain reliability through energy diversity.

The power generation industry is subject to a strong regulatory framework and is naturally risk adverse. Although demonstrations of fuel cell technology are critical to establishing the case, there are currently no satisfactory mechanisms exist to support these.

7. Discussion

As Fuel cells were found to provide major environmental, energy, and economic benefits; and as they can be used in generation, storage, automobiles, as well as in UPS systems, thus further rcsearch on them is recommended. Some of these are:

1. Incorporate a fuel cell (as an ESD) into a power system to store energy at off-peaks in order to be used in peaks.
2. Use of a fuel cell with an embedded Renewable energy source to store the energy produced (by wind, solar, or tidal powers) in order to be used when needed.
3. Develop a fuel cell to be used in UPS markets to eliminate or reduce the inconvenience of power supply quality issues.
4. Simulation of the system behaviour when fuel cells are used to supply energy for an offshore unit.
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