# ENERGY, ENVIRONMENT AND IMPORTANCE OF POWER ELECTRONICS

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*Abstract* -The technology of power electronics has practically attained maturity after four decades of dynamic evolution. In future, there will be tremendous emphasis on power electronics applications in the areas of industrial, residential, commercial, transportation, aerospace, military and electric utility systems. In the coming decades, we expect to see increasing emphasis on application-oriented R&D in system modularization, analysis, modeling, real time simulation, design and experimental evaluations. Power electronics will have increasing impact not only in global industrial automation and high efficiency energy systems, but also on energy conservation, renewable energy systems, and electric/hybrid vehicles. The resulting impact in mitigating climate change problems due to man-made environmental pollution is expected to be considerable. The paper will discuss global energy resources, climate change problems due to man-made burning of fossil fuels, and the consequences and remedial measures of climate change problems. The importance of power electronics in energy efficiency improvement, renewable energy systems, electric/hybrid vehicles and energy storage will be discussed. It will then review several applications before coming to a conclusion.

*Key-Words* - Power electronics, Energy, Environment, Climate change, Renewable energy, Energy storage. Electric/hybrid vehicles.

## 1 Introduction

Power electronics is based on fast-switching high-efficiency silicon power semiconductor devices, such as diode, thyristor, triac, GTO, power MOSFET, IGBT and IGCT, and their applications include dc and ac regulated power supplies, electrochemical processes, heating and lighting control, electronic welding, power line static VAR compensators (SVC or STATCOM) and flexible ac transmission (FACT) systems, active harmonic filters (AHF), HVDC systems, photovoltaic (PV) and fuel cell (FC) converters, dc and ac circuit breakers, high frequency heating, energy storage, and dc/ac motor drives. Motor drives is possibly the largest area of power electronics applications, and the applications include solid state motor starters, transportation, home appliances, paper and textile mills, pumps and compressors, rolling and cement mills, machine tools and robotics, wind generation systems, etc. The widespread applications of power electronics in global industrialization and high efficiency energy systems are bringing a kind of industrial revolution which is somewhat unprecedented in history. Besides industrialization, as the energy price is increasing and environmental regulations are being tightened against pollution, the applications of power electronics are spreading everywhere, particularly for energy saving, environmentally clean renewable energy generation and electric/hybrid vehicles. The role of power electronics in future will be as important as that of computers, communications and information technologies, if not more.

## 2 Global Energy

Energy is the life-blood for the progress of human civilization. Per capita energy consumption is the barometer of a nation's prosperity and living standard. It is interesting to note that per capita energy consumption in the world is highest in USA. With nearly 4% of world population (300 million out of 7 billion), the USA consumes nearly 28% of global energy, and this reflects a very high living standard (Switzerland has now the highest living standard). In comparison, China (now world's second largest economy) with nearly 19% of world population (1.3 billion), consumes approximately the same total energy as that of USA. Of course, this scenario is changing fast because of rapid industrialization of China.

Unfortunately, the world has only limited energy resources. With increasing world population and the quest for higher living standard, these resources are getting depleted fast. Fig.1 shows the idealized global energy depletion curves of fossil (coal, oil and natural gas) and nuclear (natural uranium U235) fuels of the world [1], considering the present availability and the current rate of consumption. The world has enormous reserve of coal, and at the present consumption rate, it is expected to peak at around 2070, and last around 200 years. Looking at the oil depletion curve, it appears to be near the peak now, and is expected to be exhausted in 100 years. The recent rise of oil price is natural because the demand is rising and the supply is dwindling, The natural gas reserve is expected to last around 150 years, and uranium is expected to last around 50 years (although nuclear fuel can be generated in breeder reactor). With proper conservation, these depletion curves can be extended. Discovery and exploration of new fuel resources, particularly offshore oil and gas, can provide extended depletion curves. It is believed that Arctic ocean contains world's 25% oil and gas reserves, the exploration of which can be expensive.

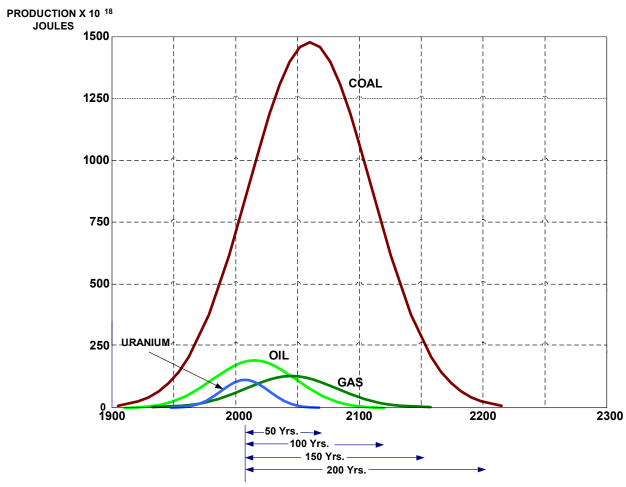


Fig.1. Idealized fossil fuel and nuclear energy depletion curves of the world (2008)

## 3 Climate Change Problems and Mitigation Methods

Unfortunately, burning of fossil fuels generates gases that cause environmental pollution problems. The more dominant effect of fossil fuel burning is the climate change problem [2][3] that is mainly caused by $CO_2$ (also methane ($CH_4$) and other gases – called greenhouse gases (GHG)), which trap solar heat in the atmosphere. The UN- IPCC (Inter Governmental Panel of Climate Change ) has ascertained with 90% certainty that man-made fossil fuel burning is the main cause for climate change (or global warming) problem. Fig.2 shows per capita emission of $CO_2$ vs. population of some selected countries. It is interesting to note that USA has the highest per capita emission in the world. The European countries typically have less than 50% emission of that of USA.

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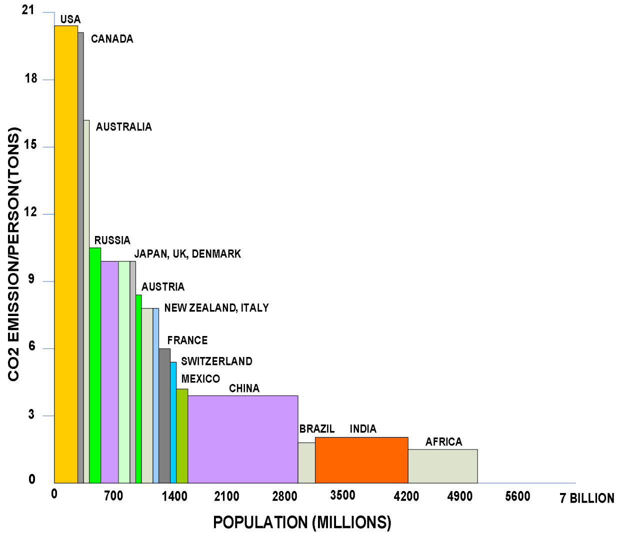


Fig.2. Per capita $CO_2$ emission vs. population of some selected countries in the world

The living standard in China is much lower than that of USA, and its per capita emission is very low. However, because of large population, the total emission (area of the rectangle) in China is higher than that of USA. Therefore, mandatory emission control for industrialized countries imposed by UN Kyoto Treaty is not working well, particularly for USA.

As mentioned before, GHG accumulate solar heat, cause global warming and raise the atmospheric temperature typically by a few degrees in 100 years [1]. The climate scientists are trying to model the climate system and predict atmospheric temperature rise by extensive simulation study on supercomputers. The most serious effect of global warming is melting ice in the Arctic, the Antarctic, Greenland, the Himalayas, and thousands of glaciers around the world that will cause inundation of low-lying areas in the world. It has been estimated that about 100 million people live within 3 ft. of sea level, and they will experience flooding of their habitats. Melting of Arctic ice is already removing the habitats of polar bears and penguins with the expected extinction of these species. Highly sensitive corals in the sea are dying due to higher water temperature and acidity of dissolved $CO_2$. The acidity effect on marine life is now under investigation. Besides sea level rise, climate change will bring severe droughts in tropical countries. This will damage agriculture and vegetation, bring hurricanes, tornedos, heavy rains and floods, and spread diseases. All these climate change effects will bring tremendous unrest and instability in the world. Considering the serious consequences, the UN Kyoto Protocol emerged in 1997 that tends to limit emission of different countries within a certain quota. The climate change problems can be solved or mitigated by the following measures: (1) Promote all energy consumption in electrical form. Power generating stations burning fossil fuels can implement emission control methods, and any new invention on emission control can be applied. This is better than distributed consumption of fossil fuels; (2) Reduce or eliminate coal-fired power generation; (3) Increase nuclear power. However, nuclear power has safety and radioactive waste disposal problems; (4) Preserve rain forests and promote reforestation since trees absorb $CO_2$; (5) Control human and animal population, since they exhale GHG. Besides, larger population means more energy consumption. This method is not easy; (6) Promote generation of environmentally clean energy; (7) Replace ICE vehicles by EVs/HEVs; (8) Promote mass electrical transportation; (9) Save energy by more efficient generation, transmission, distribution and utilization of electricity; (10) Finally, energy wastage should be prevented, and its consumption should be economized to make the life style simpler. It has been estimated that almost one-third of our energy consumption can be saved by this method.

## 4 Why Power Electronics is so Important?

Power electronics deals with conversion and control of electrical power with the help of switching mode power semiconductor devices, and therefore, the efficiency of power electronics based equipment can be very high (98-99%). With the advancement of technology, as the cost of power electronics is decreasing, size is becoming smaller and the performance is improving, the application of power electronics is expanding in industrial, commercial, residential, aerospace, military, transportation and utility systems. In industrial applications, power electronics helps productivity and product quality improvement. One important role of power electronics that is being increasingly visible now is the

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energy saving by improving energy efficiency improvement of electrical apparatus. Again, power electronics is being increasingly important in renewable energy generation, utility system energy storage and electric/hybrid vehicles. These will be explained in the next few sections.

### 4.1 Energy Saving

Saving of energy by power electronics gives the financial benefit directly. The extra cost of power electronics can be recovered in a period depending on the cost of electricity. Again, reduced consumption means reduced generation that indirectly mitigates environmental pollution and climate change problems if the energy is generated by burning fossil fuels. In USA, roughly 60% of grid energy is consumed in electric motor drives, and 75% of these are pump, fan, and compressor-type drives. The majority of these drives in industrial environment are for control of fluid flow. In such applications, instead of using the traditional flow control method by variable throttle or damper opening with a constant speed induction motor, variable frequency variable speed motor with fully open throttle can save energy up to 20% at light load [4]. Again, since most of the time the drives operate at light load, flux programming control at light load can give further improvement of drive efficiency. Power electronics-based load-proportional speed control of air-conditioner/heat pump can save energy by up to 20%. Power electronics based electric/hybrid vehicles save energy not only by regenerative braking but additional efficiency improvement of electrical drive. One popular application of power electronics in recent years is variable frequency drive in diesel-electric ship propulsion, which can save considerable amount of fuel compared to traditional diesel-turbine drive. Around 20% of grid energy in USA is used for lighting. Instead of incandescent lamps, power electronics based compact fluorescent lamps (CFLs) typically give four times more energy efficiency, besides having longer (ten times) life. Currently, the emerging solid-state LED lamps consume 50% less energy than CFLs and have five times longer life. Our present electric power grid will be replaced by smart or intelligent grid in future that will extensively use state-of-the-art power electronics, computers and communication technologies and will permit optimum resource utilization, economical electricity to consumers, higher energy efficiency of generation, transmission and distribution system, higher system reliability by improved fault management and improved system security. It has been estimated that widespread efficiency improvement by power electronics and other methods with the existing technologies can save up to 20% of global energy demand, and another 15-20% can possibly be saved by eliminating waste.

### 4.2 Renewable Energy Systems

Renewable energy resources, such as hydro, wind, solar, biofuels, geothermal, wave and tidal powers, are environmentally clean (green) and abundant in nature, and therefore, are getting widespread attention all over the world. Scientific American recently published a paper [7] that predicts that renewable energies only (with adequate storage) can supply all the energy needs of the world. The wind and solar photovoltaic (PV) resources, particularly, are dependent on power electronics for power conversion and control, and are important to meet our growing energy needs and mitigate the climate change problems.

#### 4.2.1 Wind Energy

In a wind generation system, the variable frequency variable voltage power from the wind turbine-generator are converted to constant frequency constant voltage power before feeding to the grid, or for autonomous system. The world has enormous wind energy resources, and they are the most economical green energy (almost comparable to fossil fuel power). According to the estimate of Stanford University [9], exploitation of only 20% of the available (but economical) resource can supply all the electricity needs of the world. Wind and PV energy are particularly important for the 30% of world population that lives outside the power grid. Currently, Denmark is the leader with 20% electricity generation by wind, which is expected to grow to

40% by 2030. In terms of total installed capacity, China is the leader which is followed closely by USA, Germany and Spain. The USA, currently, generates 2% electrical energy from wind, which is expected to grow to 20% by 2030. A drawback of wind energy is that it is sporadic in nature, and therefore, may need backup power from fossil or nuclear plant, or bulk storage of surplus wind energy. The cost of wind energy depends on onshore or offshore installation, pattern of wind flow (utilization factor), and the length of transmission for feeding to the main grid.

### 4.2.2 Photovoltaic Energy

Silicon photovoltaic devices convert sunlight directly into electricity. Of course, solar thermal energy can also be used through concentrators that generate steam and operates turbo-generators to generate electricity. The PV generated dc is converted to ac and fed to the grid, or used as autonomous load. The PV devices have the advantages that they are static, safe, reliable, environmentally clean, and do not require any repair and maintenance like the wind generation system. Although, with the current technology, PV power is more expensive than wind power, the aggressive R&D is reducing the PV cost significantly. The IEEE has ambitious prediction that by 2050 PV will supply 11% of global electricity demand. Unfortunately, like wind power, PV is also sporadic and requires backup energy source or bulk storage. Or else, the recent smart grid concept can shift consumer's energy demand (demand-side management) with the help of smart metering and attractive tariff so that the demand curve tends to match with the available curve. Currently, there are ambitious plans to explore solar energy from the African deserts like Sahara and Kalahari through extensive PV installations and tying to the European grid through HVDC transmission.

## 4.3 Energy Storage for Utility System

There are a number of possible bulk energy storage methods for utility system [8] which can be summarized as follows:

**4.3.1 Pumped Storage –** In this method, hydroelectric generators are used as motor pumps to pump water from tail to head of a reservoir using off-peak cheap grid energy. At peak demand, the head water runs the generator to supply the demand. At favorable site, it can be cheapest method of storage, and is widely used in the world.

**4.3.2 Battery Storage –** Although very expensive, this is the most common method of storage for the grid. In this method, electrical power from the grid is rectified to dc that charges the battery. The stored energy is then retrieved through the same rectifier acting as inverter. The cycle efficiency is high. Lead-acid battery has been used extensively, but recently, NiCd, NaS, Li-ion and Vanadium redox flow battery are finding favor. Flow battery has fast response and can be economical for large storage.

**4.3.3 Flywheel Storage (FW) –** In this method, electrical energy from the grid is converted to mechanical energy through a converter-fed drive that charges a flywheel, and then energy is recovered by the same system operating in generator mode. The FW can be placed in vacuum or in $H_2$ medium, and active bearing can be used to reduce energy loss. Steel or composite material has been used in FW to withstand stress due to high speed of FW. FW storage can be somewhat economical, but mechanical storage has the usual disadvantages.

**4.3.4 Superconducting Magnet Energy Storage (SMES) –** In SMES, the grid energy is rectified to dc that charges SMES coil to store energy in magnetic form. Then energy is then retrieved by the reverse process. The coil is cooled cryogenically so that its resistance tends to be zero. Either liquid Hilium ($0^0$ K) or liquid Nitrogen ($77^0$K) can be used.

**4.3.5 Ultracapacitor Storage(UC) -** An UC is an energy storage device like electrolytic capacitor, but its energy storage density can be as high as 100 times higher than that of electrolytic capacitor. The power density of UC is very high and large amount of power can cycle through it without reducing it's life time. The technology is not yet mature for bulk energy storage.

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**4.3.6 Vehicle-to-Grid Storage (V2G)** – This is a new concept for bulk energy storage assuming that a large number of EV batteries are connected to the grid. An EV battery can temporarily store grid energy which can be recovered in peak demand hours. However, the disadvantage is that battery life is shortened by charge-discharge cycles.

**4.3.7 $H_2$ Gas Storage –** Off-peak grid energy can be used to generate $H_2$ gas by electrolysis. The $H_2$ gas can then be used as fuel in fuel cells or directly burnt in an ICE. This is the concept of future Hydrogen Economy. The cycle conversion efficiency is somewhat poor. $H_2$ gas can be generated easily by using surplus and abundant renewable energy sources and stored as compressed or liquefied gas at high density. Compressed gas can be stored in caverns, salt domes, depleted oil or gas fields.

**4.3.8 Compressed Air Energy Storage (CAES) –** This is another method of grid energy storage where off-peak or renewable energy generated electricity can be used to compress air and store underground. At high demand of electricity, the compressed air is heated and mixed with natural gas to burn in turbine to generate electricity. CAES has been used successfully in Europe.

### 4.4 Electric/Hybrid Vehicles

In EV, generally, battery is the energy storage device. The dc is converted to variable frequency variable voltage ac with the help of power electronics to run the propulsion motor (induction or synchronous motor). The braking energy can be easily regenerated to recharge the battery. In a HEV, the battery is assisted by a power device (usually gasoline ICE). The range in EV is limited by battery capacity, but in HEV, there is no such problem. Unfortunately, battery technology today is not yet mature. It is bulky, expensive, has limited cycle life and long (several hours) charging time. Although Ni-MH batteries have been used extensively, currently, Li-ion batteries have penetrated in the market. It has large storage density, but expensive. There is large emphasis on Li-ion battery research in recent years. Currently, a number of Li-ion battery based EVs/HEVs have been introduced in the market.

### 4.4.1 Comparison of Battery and Fuel Cell EV

Currently, R&D for both battery EV and fuel cell (FC) EV are progressing in parallel. Therefore, it is worth making comparison between the two technologies. Fig. 3 summarizes the comparison in today's technology for mass production with identical 300 miles range and assuming that both deliver 60 kWH to the wheels [10].

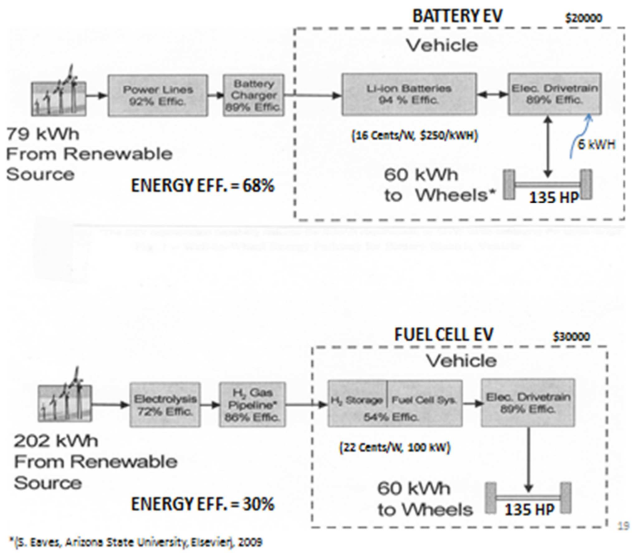


Fig.3. Comparison of battery electric vehicle with fuel cell electric vehicle

The battery EV is assumed to have the battery charging from clean wind energy (although currently it is mostly from coal or nuclear), which is required to supply 79 kWH with power lines efficiency of 92%, battery charging efficiency of 89%, battery efficiency of 94%, and drive train efficiency of 89%, as indicated in the figure. Typically, 6 kWH of regenerated energy has been considered in the calculation. The total energy efficiency of battery EV is calculated as 68%. The estimated cost of the vehicle is $20,000 with battery cost of $0.16/W and $250/kWH (somewhat optimistic). In FC EV, as shown in the figure, wind energy is also used to generate $H_2$ by electrolysis. $H_2$ gas, stored on the vehicle, is used in FC (PEMFC) to generate electricity that runs variable frequency drive

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system. The auxiliary storage (battery or UC) at the FC terminal has been ignored for simplicity. Considering all the efficiency figures of FC EV, the total energy efficiency is only 30%, i.e., 202 kWH is to be supplied from wind generation system. The cost figures of FC EV are shown on the figure. In summary, FC EV is 38% less efficient, 43% more weight and 50% more expensive (even ignoring the cost of auxiliary storage). Considering the disadvantages, FC EV research has recently been backed down in USA.

## 5 Some Example Applications

### 5.1 HVDC System for Wind Park Interconnection

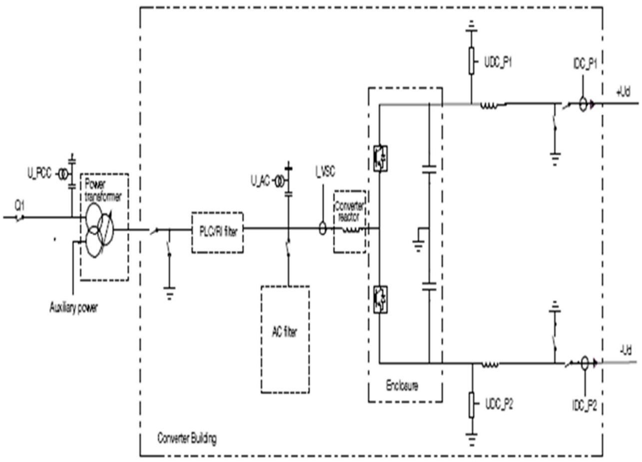


Fig.4. High Voltage DC (HVDC) system for offshore wind park interconnection with the German grid (ABB HVDC LIGHT –NordE.ON 1)

Fig.4 shows the simplified diagram of HVDC transmission system (NordE.ON1)[13] for world's largest offshore wind park (450 MW) in North Sea that is interconnected to the German grid. Generally, wind parks are located away from load centers, and therefore, require high voltage transmission before connecting to the grid. The above system has been built by ABB Company using HVDC LIGHT technology. The park feeds ac power at the sending station on the left, where the voltage is boosted by a 3-winding transformer (to supply auxiliary power), and feeds a back-to-back voltage-fed PWM converter system (only the sending end is shown in simplified form) before connecting to the high voltage grid at the receiving station on the right. The intermediate double-circuit underground HVDC transmission system (±150 kV, 200 KM) is partly undersea and partly underground. Each converter unit is a 3-phase 2-level PWM voltage-fed IGBT module converter, where a large number of matched high voltage devices are connected in series-parallel to share the large voltage and power. The IGBT has the advantage of current limiting, high switching frequency (2.0 kHz) and fast switching capability to force proper voltage and current sharing of the devices. The voltage-fed system has the advantages of multi-terminal capability, control of active and reactive power independently, and mitigation of flicker or grid instability by fast reactive energy control. The 3-winding transformer with on-load tap changing and zero sequence voltage injection permits dc voltage to be maximum for high power line efficiency and maximum power capability.

### 5.2 400 MW Hydro/Pumped Storage

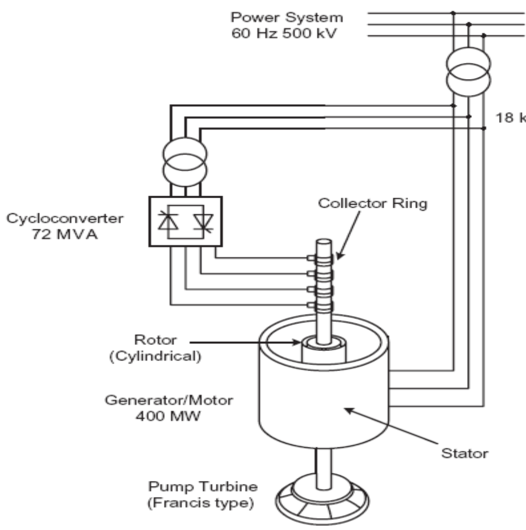


Fig.5. Variable speed hydro generator/pump storage system in Kansai Electric Power Co, Japan

Bulk energy storage by pumped storage method was mentioned in Section 4.3. Fig.5 shows the 400 MW variable speed Scherbius drive system for hydroelectric generator/pumped storage system installed in Ohkawachi plant of Kansai Power Co.[14]. As the water level in the head changes in both generating and motoring mode, the synchronous

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speed (360 RPM at 60 Hz) of the wound-rotor induction machine changes in subsynchronous and supersynchronous modes to improve the energy efficiency of the drive system. The 72 MVA thyristor phase-controlled cycloconverter changes the slip power in either direction to control the machine speed maintaining the drive power factor always at unity. In the daytime, the machine runs as a hydro generator feeding electricity to the grid. At night, when utility power demand is low and surplus grid power is available, the machine runs to pump water from the tail to the head storage reservoir. This is the world’s first and only variable speed generator/pump system. Toshiba built a large FW energy storage system on the same principle, where the water turbine was replaced by a FW.

### 5.3 10 MVA Battery Storage

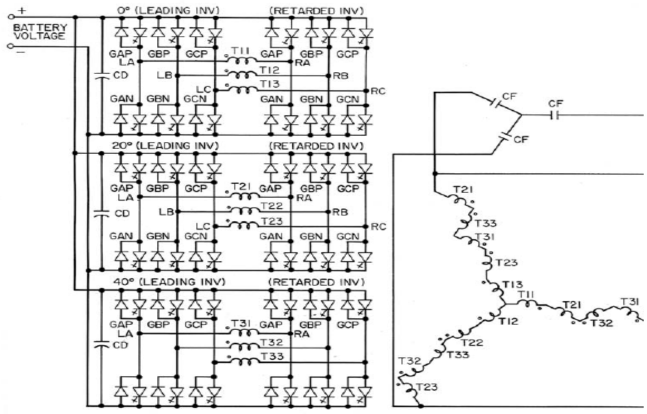


Fig.6. 10 MVA battery storage converter system for utility grid
(Southern California Edison Grid)

Fig.6 shows the 10 MVA GTO converter system [15] for Southern California Edison electric grid’s battery storage plant using off-peak grid power. The 60 Hz grid power is converted to dc and stored in the lead-acid battery bank. When the grid power demand rises beyond the system generation capacity, the battery energy is converted back to ac (converter acts as inverter) to supply the stored energy to the grid. At no load, the converter system can act as static VAR compensator (SVC, SVG, or STATCOM) (leading or lagging) that can regulate the system voltage and stabilize the power system. The 18-step converter system uses phase-shift voltage control principle [4] to fabricate the 18-step output voltage wave by using three groups of H-bridges with $0^0$, $20^0$ and $40^o$ phase leads, respectively. The 3-phase multi-winding 60 Hz transformer combines the phase-shifted voltages, boosts the voltage, and provides isolation from the utility system. The harmonics ($17^{th}$, $19^{th}$, etc.) in the 18-step wave are filtered by a capacitor bank. The magnitude and phase angle of the output voltage can be controlled by phase shift to control active power in either direction and reactive power at the output. Note that GTO converter operates at low frequency (60 Hz) because of excessive switching loss of the device.

### 5.4 Fuzzy Control of Wind Generation System

Fuzzy logic is an artificial intelligence (AI) technique that provides robust adaptive control response of a drive with nonlinearity, parameter variation and load disturbance effects. Fig.7 shows fuzzy logic based efficiency optimized adaptive control of a variable speed wind generation system [16]. The variable speed wind turbine on the left is coupled to a cage type induction generator, and the variable frequency

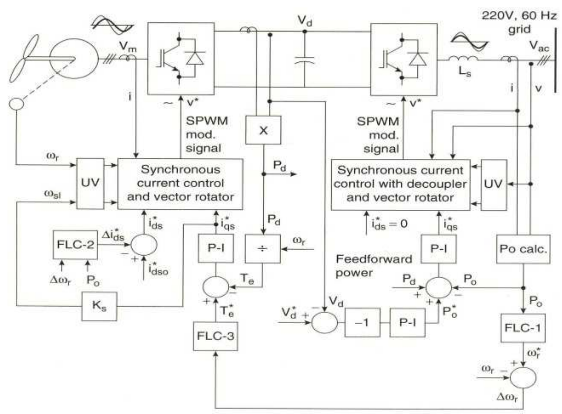


Fig.7. Fuzzy logic based efficiency optimized control of variable speed wind generation system

variable voltage power is converted to 220 V, 60 Hz power by a back-to-back PWM voltage-fed converter system, and fed to the utility grid. The generator speed ($\omega_r$) is controlled by indirect vector control to track the variable wind velocity to extract the maximum aerodynamic power. Machine flux ($\Psi_r$) is programmed by the excitation current ($i_{ds}$) in open loop manner. The line-side converter is direct vector-controlled with voltage ($V_d$) control in the outer loop and power ($P_0$) control in the inner loop. The control system uses three fuzzy controllers: (1) FLC-1, for online search of generator speed to maximize the output power, (2) FLC-2, for online search of machine excitation current ($i_{ds}$*) to optimize generator efficiency at light load; and (3) FLC-3, for robust control of generator speed. Fig.8 explains the performance of the fuzzy controllers in Fig.7. Neglecting the system losses, line power output ($P_0$) of the generating system at different generator (or turbine) speed (neglecting gear ratio) at different wind velocity ($V_w$) is shown in the figure. Assuming the initial wind velocity is steady at $V_{w4}$, and generator speed at $\omega_{r1}$, the output power power is at A. The activation of FLC-1 control alters the generator speed to $\omega_{r2}$, where $P_0$ is maximum at B. At the termination of FLC-1 control, FLC-2 is activated, which increases $P_0$ further to point C. If wind velocity increases to $V_{w2}$, the power jumps to the point D. Then, sequential control of FLC-1 and FLC-2 raises the power to F. If at this point, wind velocity decreases to $V_{w3}$, the locus of operation is indicated on the figure. If during the optimization search, wind velocity changes, the search is abandoned.

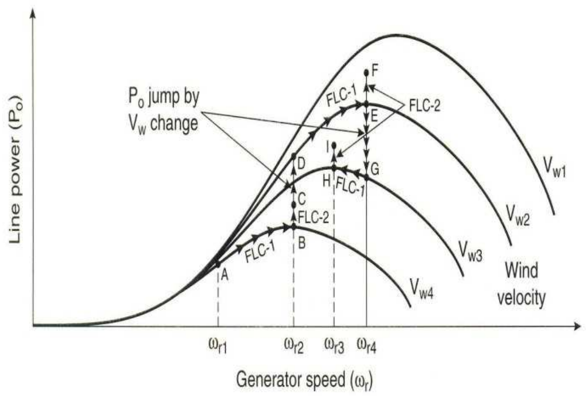


Fig.8. Performance of fuzzy controllers (FLC-1 and FLC-2) to optimize line power output

## 6 Conclusion

The paper reviews the global energy scenario and climate change problems due to man-made burning of fossil fuels and summarizes the possible mitigation methods. It then discusses the impact of power electronics in energy conservation, renewable energy systems (wind and PV), bulk storage of energy and electric/hybrid vehicles. Finally, application examples on HVDC wind park interconnection, variable speed hydro/pump storage system, battery storage system, and fuzzy controlled wind generation systems have been described.

Power electronics has now established as a major discipline in electrical engineering, and is now merging as a high tech frontier of power engineering. It appears that the role of power electronics in our society in future will be as important as computers, communication and information technologies today.

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